Critical Factors to Consider in Purchasing for a Sustainable Inbound Supply Chain

A Perspective on Large Scale Lithium-ion Battery Manufacturing

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Critical Factors to Consider in Purchasing for a Sustainable Inbound Supply Chain

A Perspective on Large Scale Lithium-ion Battery Manufacturing

Master Thesis

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Kritiska faktorer att ta hänsyn till i inköpsprocessen för en hållbar värdekedja

Ett perspektiv på storskalig litiumjonbatteritillverkning

Examensarbete

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KTH Industriell teknik och management
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Abstract

Together with electrification of the transportation sector and the introduction of renewable energy in the electricity grid, the demand for lithium-ion batteries is increasing. As a result of this emerging need, large-scale battery manufacturing is a promising and developing industry. Currently, there exist a challenge for lithium-ion battery manufacturers to ensure supply of the desired material and to guarantee operation in a sustainable manner. The material included in a battery cell possess unique characteristics, has high criticality, and experience limited availability, which has resulted in an uncertain business environment with high complexity. Hence, the aim of this thesis is to investigate how unique material characteristics affect the purchasing environment and can be considered to obtain a sustainable inbound supply chain for lithium-ion battery manufacturers. The study is based on the following research question; How can purchasing of critical direct material for lithium-ion battery manufacturers support a sustainable inbound supply chain?

This research is performed in collaboration with Northvolt AB, a company that plans to build Europe’s largest lithium-ion battery manufacturing facility in 2018. Based on two approaches, one focusing on the technical context of lithium-ion batteries and one focusing on the related purchasing environment, this study explores how different critical material affects the supply risk. Assessment of important sustainability factors, as well as development of possible supply risk mitigation strategies are performed based on multiple interviews conducted with industry experts. A central contribution of this exploratory research is the theoretical assessment of material criticality in purchasing, as well as the empirical description of the existing challenges lithium-ion battery manufacturers are facing today.

It is concluded that lithium-ion battery manufacturers are operating in a unique context by being exposed to potential supply disruptions that have severe impact on the operation. This study indicated that 65 percent of the material in lithium-ion batteries are ranked with high strategic importance, due to high profit impact while suffering from severe supply risk. It is recommended that Northvolt and other lithium-ion battery manufacturing companies implement risk mitigation strategies to guard against potential disruptions. This research specifically highlights vertical integration and establishment of long-term agreements with significant actors, as the most prominent ones. It is additionally recommended to include sustainability considerations in the material and supplier selection process, in order to obtain a sustainable inbound supply chain.
Sammanfattning

I samband med elektrifiering av transportsektorn och en växande andel förnyelsebar energi i det befintliga elnätet, ökar även behovet av litiumjonbatterier. Till följd av denna utveckling är storskalig batteritillverkning helt nödvändigt och en industri som utvecklas i snabb takt. Det ökande antalet batteritillverkande företag, i kombination med ett begränsat utbud av de batterispecifika materialen har dock lett till en obalanserad marknad. Flertalet av de ingående materialen är kritiskt rankade och av unik karaktär, vilket utgör en utmaning för batteritillverkare att säkerställa materialanska ning på ett hållbart sätt. Målet med denna studie är att undersöka hur de olika kritiska direktmaterial och dess karaktärer påverkar inköpsprocessen, samt vilka faktorer som måste tas hänsyn till för att säkerställa en hållbar värdekedja. Studien baseras på följande forskningsfråga; **Hur kan inköp av kritiska direktmaterial stödja en hållbar värdekedja för litiumjonbatteritillverkare?**


Studien konstaterar att litiumjonbatteritillverkare verkar i ett unikt företagsklimat, genom att vara utsatta för betydande risker som kan ha omfattande konsekvenser. Den genomförda analysen visar på att 65 procent av de ingående materialen kan klassificeras som strategiskt viktiga då de har stor ekonomisk inverkan samt ingår i en värdekedja som är utsatt för betydande risker. Slutligen, rekommenderas Northvolt och liknande batteritillverkande företag att implementera strategier för att minimera den potentiella inköpsrisken. Ökad vertikal integration, samt etablering av långsiktiga överenskommelser med externa aktörer är det som visat sig vara mest relevant. Dessutom bör hållbarhetsaspekter inkluderas tidigt i inköpsprocessen, redan vid urval av både material och leverantörer för att säkerställa en hållbar värdekedja.
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1. Introduction

The aim of this chapter is to provide an introduction to the thesis background, problematization, and objective. It further presents the study’s research question, scope and outline.

1.1. Background

The energy sector is facing challenges of limiting greenhouse gas emissions, reducing the dependence of fossil sources and introducing renewable energy to the existing energy system [Tamburrano et al. 2016]. The European Union has set the target to cut its greenhouse gas emissions by 20 percent by 2020 compared to 1990 levels, and to have a 20 percent share of total energy consumption that originates from renewable energy [European Commission 2015]. A key element in meeting these sustainability goals is the development of energy storage technologies [Matseelar et al. 2014]. In this transition, electrochemical energy storage in batteries will play a crucial role due to its favorable features such as pollution-free operation and low maintenance [Tarascon et al. 2011]. The Swedish Energy Agency expects the need for batteries to be greater than ever before when it comes to applications in transportation, renewable energy storage as well as system service for the electricity grid [Energimyndigheten 2016].

1.1.1. Increasing Demand for Lithium-ion Batteries

Among various types of batteries available, lithium-ion batteries are the most promising and fastest growing battery chemistry [Lundgren 2015; Pillot 2016]. Since the last two decades, lithium-ion batteries can be considered as the modern electrochemistry’s most impressive success story [Etacheri et al. 2011]. Lithium-ion batteries are favorable in comparison with other battery technologies due high energy and power output, which make them lighter and smaller than other rechargeable batteries with the same energy storage capacity [Pode and Diouf 2015]. Today, the primary use of lithium-ion batteries is in consumer electronics [Santhanagopalan et al. 2016] but the characteristics also make them suitable for operation in several other applications, such as supporting off-grid renewable energy or acting as an energy source in electric vehicles [Pode and Diouf 2015].

The market for lithium-ion batteries is expanding, but for the technology to be fully adopted, there is a need for price reductions [Pode and Diouf 2015; Swart et al. 2014]. The primary driving force to making lithium-ion batteries affordable is believed to be the foreseen expansion of electrical vehicles. This will accompany the mass production of lithium-ion batteries and make them affordable as a benefit of large-scale production [Pode and Diouf 2015]. A decrease in battery costs have started to occur and the price has been reduced by a factor four, from about 1000 USD per kWh in 2008 to 268 USD per kWh in 2015 [IEA 2016]. However, in order for lithium-ion batteries to develop in the commercialization of electric vehicles, the price must be reduced to at least 125 USD per kWh for the big breakthrough to take place [Daniel et al. 2014; IEA 2016].
1.1.2. Large-Scale Lithium-ion Battery Manufacturing

The lithium-ion battery industry has seen a rapid development the last couple of years, and the future demand is expected to continue to dramatically grow and gain market share. Figure 1.1 illustrates the development of the lithium-ion battery manufacturing industry based on an estimation of future demand and market share forecasts. However, the implementation of lithium-ion batteries in a larger scale is hindered by issues such as safety, cost, and materials availability, which still need to be resolved [Scrosati and Garche 2009].

![Figure 1.1: Lithium-ion battery demand and market share forecast by Hocking et al. [2016]](image)

Producing high-quality products, while minimizing the manufacturing costs are continuing to be the challenges that the industry is facing. The included materials, as well as the manufacturing processes, require top quality and extreme precision in many ways, which adds complexity to every step in the operation. The past decade has already shown performance improvements and rapid cost declines in battery manufacturing due to heavily R&D investments, technology learning and mass production [IEA 2016]. As a result of economies of scale and an even more innovative production with reduced waste, the future battery cost is expected to be further reduced [Durbin 2016]. The best way in order to achieve popularization and to make the lithium-ion cells safer and more price competitive is to have a highly automated production [Helou and Brodd 2012]. Efficient manufacturing processes in large-scale is a crucial aspect of the development of lithium-ion batteries, however the amount of manufacturing investments are still not sufficient to meet the future forecasted demand.

In 2015, the market for lithium-ion batteries was dominated by a few large battery manufacturers and essentially all large-scale production of lithium-ion batteries were based in Asian countries. Japan, China and Korea represented 88 percent of the global lithium-ion manufacturing capacity for all end-user applications [Santhanagopalan et al. 2016]. With the majority of existing battery manufacturers located in Asia and on-going projects in the United States, there is no key player in Europe. Northvolt
AB is a recently established company that plans to build a large-scale battery facility in Sweden with a capacity of 32 GWh, in order to supply Europe with lithium-ion batteries. The construction of the plant is planned to start in 2018 [Bederoff 2017], with the first cell produced as of the year 2020 [Fredelius 2017]. The large access to renewable energy in Sweden makes it one of few countries, along with Norway and Iceland, where it is possible to produce an entirely green battery with zero emission energy [Energikommissionen 2016], providing a favoring condition for a lithium-ion battery manufacturing facility in Sweden.

### 1.2. Problematization

The increasing amount of lithium-ion battery manufacturing facilities creates a new environment for the operating battery manufacturers, which is followed by an emerging demand for the needed materials included in a battery cell. Together with the increasing material demand there exist a limited amount of available suppliers that offer the required battery purity grade, which has resulted in challenges for lithium-ion battery manufacturers to secure a supply of material. Furthermore, many of the critical materials are associated with sustainability issues as a consequence of their risk for resource depletion, as well as dependency on countries with high social risk. This raises a need for establishing a sustainable supply chain that contributes to economic growth, environmental protection and social well-being. This study focuses on the phenomenon of how purchasing of critical direct material can support a sustainable inbound supply chain for lithium-ion battery manufacturers. Peter Carlsson, CEO at Northvolt express the related challenge accordingly:

*One of the main challenges that lithium-ion battery manufacturers face today is how to secure the supply of critical material included in a battery cell. The material needs to meet the highest quality demand, while still being sourced in a sustainable way in order to be competitive over the long term*

- Peter Carlsson (2017), CEO, Northvolt

Purchasing of material is a necessary area for lithium-ion battery manufacturers to allocate resources because of the fact that direct material represent the largest share of total battery cell cost, ranging from 70-80 percent in automated production [Helou and Brodd 2012; Santhanagopalan et al. 2016]. Additionally, the material’s technical attributes are crucial for the battery’s overall performance, which needs to be taken into careful consideration in the purchasing process. As a result of the rapid increase of battery manufacturers, the purchasing environment is transforming and the high supply risk associated with many of the included materials can lead to substantial consequences for the company. This needs to be assessed in order to mitigate increased vulnerability, and unwanted disruptions in the inbound supply chain. Furthermore, Lapko et al. [2016] suggest that supply disruption events in the future need to be proactively considered and addressed, thus highlighting the necessity of this research.
1.3. **Objective and Research Question**

The aim of this study is to investigate how unique critical material characteristics affect the purchasing environment and can be considered to obtain a sustainable inbound supply chain for lithium-ion battery manufacturers. The following research questions are analyzed:

**Research Question**

- How can purchasing of critical direct material for lithium-ion battery manufacturers support a sustainable inbound supply chain?

**Sub-Research Questions**

- SRQ 1: What are unique characteristics for critical direct materials in lithium-ion batteries?
- SRQ 2: How do these specific material characteristics affect the purchasing environment?
- SRQ 3: What are critical factors for lithium-ion battery manufacturers to consider in purchasing to obtain a sustainable inbound supply chain?

1.4. **Scope of Thesis**

This study is specifically focused on purchasing of material to a cylindrical lithium-ion battery cell with a ternary chemistry. The chosen chemistry has gained attractiveness since the introduction in 2001 [Arnold et al. 2015] and are believed to be relevant over time. It additionally has many advantages such as high energy and power densities, high specific capacity, and good thermal stability. These promising attributes are the reasons for why this research is focused on the specific cell chemistry. Other types of including materials in different battery chemistries are not taken into consideration in this research.

The research focuses on the topic of purchasing critical direct material, grouped into clusters of minerals, metals, and chemicals. The materials within the scope of this study are defined as critical for lithium-ion battery manufacturers and included in the analysis because they play a noteworthy role for the cell performance and represent a large cost. Hence, the supply of these materials are of the most importance. Purchasing of other materials that are necessary for the operation of lithium-ion battery manufacturers are intentionally left out. Theoretical frameworks from previous literature have been used to assess the material criticality, covering the supply risk related to economic, environmental and social challenges. The evaluation criteria are based on the literature review in combination with the conducted interviews in regard to the applicability to this specific research.

Finally, the analysis performed in this research is made from an industry-level system perspective, rather than company specific. The research is performed in collaboration with Northvolt AB but
focuses mainly on the overall industry of large scale lithium-ion battery manufacturing. Specific vendors, suppliers and other providers are not central in this report, but rather the challenges that are general for the industry.

1.5. Disposition

The thesis is outlined according to the following structure:

- **Introduction**: This chapter presents the background to the research problem and highlights the need for the study. It further includes the objective and research question that is addressed, as well as the scope of the thesis.

- **Purchasing of Critical Material**: This chapter focuses on previous research of critical material purchasing. It also includes sustainability factors and different supply risk mitigation strategies. The conducted theories work as a theoretical reference that is applied on the lithium-ion battery manufacturing industry.

- **Research Methodology**: This chapter presents the research design and the methods for data collection and analysis that are applied in this study. It further discusses how reliability, validity, generalizability, and ethics are considered throughout the process.

- **Lithium-ion Battery Manufacturing**: This chapter gives a background of lithium-ion battery technology and the critical materials that make out the necessary context for the research. The related environmental and social impacts for the materials are additionally addressed.

- **Findings and Analysis**: This chapter presents the findings from the empirical study. An analysis of how the critical direct material affect the purchasing environment is presented with respect to sustainability consideration, as well as supply risk mitigation strategies.

- **Discussion**: This chapter discusses the gathered findings and results based on the study’s research questions. The empirical findings are concluded and compared with the already existing research.

- **Conclusion**: This chapter concludes the research and discusses how it fulfills the objective. It further presents the theoretical and empirical contribution, managerial implications and suggests further research.
2. Purchasing of Critical Material

This chapter covers the field of study related to purchasing of critical material for lithium-ion battery manufacturers and presents a theoretical reference for this study. Relevant literature is conducted within the field of material purchasing, classification of materials, sustainability and supply risk mitigation strategies. The analyzed theories have been revised during the research process, allowing empirical findings to impact this chapter’s content.

2.1. Material Purchasing

Purchasing of material is a crucial activity for manufacturing companies and impacts the entire business. A common framework that is used to indicate various purchasing environments with the need for different purchasing strategies is the matrix developed by Kraljic [1983]. The matrix is considered as the big academical breakthrough within professional purchasing and has inspired many researchers to further develop theories in various purchasing models [Canils and Gelderman 2005]. Besides acting as an operational function, the purchasing process has a strategic importance for supply management, which should be taken into consideration by companies. This is particularly important in environments where the importance of purchasing is high and the supply market is complex [Kraljic 1983].

The Kraljic Matrix assists purchase managers to classify the purchased material and to identify the related purchasing environment. According to the classification of a material’s profit impact and supply risk the position in the matrix vary. The different material classifications represent unique purchasing environments and are illustrated in Figure 2.1. The definitions made by Kraljic [1983] can be described accordingly: leverage items have high profit impact with low supply risk and purchasing power should be exploited, strategic items have high profit with high supply risk and for these materials partnerships should be formed, non-critical items have low profit impact with low supply risk and efficient

![Figure 2.1. Illustration of the Kraljic matrix. Adapted from Kraljic [1983]](image-url)
processing should be ensured, finally bottleneck items with low profit impact and high supply risk requires to assure supply. Kraljic [1983] suggests an analysis of the supply market in terms of supplier power versus company strengths, which in turn provides a foundation for purchasing strategies and suitable actions for the different material. A similar approach to assess the purchasing environment is defined by Weele [2010]. He states that the purchasing process is affected by the characteristics and the strategic importance of the product, the amount of money involved in the purchase, the purchasing market, and the related degree of risk.

The model proposed by Kraljic [1983] has been criticized for reducing the purchasing issues to only two dimensions; profit impact and supply risk, resulting in that the model does not capture all aspects. Sustainability is a dimension that is not originally addressed in the Kraljic model but a concern for many companies in the purchasing process. When sustainability concerns are important drivers for procurement decisions, the strategic impact of considering these issues may cause some suppliers to be positioned in different areas of the matrix [Cousins et al. 2008]. Therefore a third dimension of the Kraljic matrix for environmental costs in each sector is suggested by Cousins et al. [2008] and further developed by Pagell et al. [2010] who propose a modification of the Kraljic model to additionally consider both environmental and social aspects. The revision of the model is based on the Triple Bottom Line, established by the Brundtland Commission [1987] definition of sustainable development, and covers the ability to interpret and manage economic growth, environmental protection, and social risks in different activities.

### 2.2. Classification of Materials

Classification of material in accordance with the model described above lays the ground for purchasing decisions and strategies. The classification itself is important since the criticality of materials can create an uncertain business environment for companies, and threaten the continuity of production operation which might result in bottlenecks for the deployment of certain technologies [Lapko et al. 2016]. The Kraljic model can be compared with more recent studies by Reuter [2016] who uses an approach to characterize raw material’s criticality by applying two quantitative indicators; (1) supply risk, which expresses the probability of material shortage; and (2) vulnerability, which indicates the severity of material shortage. This approach expresses the extent of potential material supply shortage with respect to production hold-ups and the supply risk for a required material. A shortage in material supply can cause significant negative impacts on the production and business operation for an entire industrial sector [Reuter 2016]. Based on reviewed literature, the classification of material included in this chapter is grouped in to three main areas; profit impact, supply risk, and sustainability. These are summarized in 2.1 together with identified driving factors.
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<td><strong>Profit Impact</strong></td>
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</table>
| Percentage of total cost | European Commission [2014], Kraljic [1983]  
  *Price increase and fluctuations: Graedel et al. [2012], Porter [1979], Slowinski et al. [2013]*  |
| Business importance    | Lapko et al. [2016], Graedel et al. [2012]  
  *Impact on product quality or business growth: Kraljic [1983].  
  Enabling economic growth: European Commission [2014]* |
| **Material availability** | Alonso et al. [2007], Crocker et al. [2011], Graedel et al. [2012], Kraljic [1983], Slowinski et al. [2013],  
  *Geological unavailability: Beer [2015], Craighead et al. [2007]* |
| **Supply market structure** | Beer [2015], Graedel et al. [2012], Kraljic [1983], Lapko et al. [2016], Porter [1979], Slowinski et al. [2013], Weele [2010]  
  *Cost of changing supplier: Meixell and Norbis [2011].  
  Competitive demand: Alonso et al. [2007]* |
| **Geopolitical supply risk** | Beer [2015], European Commission [2014], Gemechu et al. [2015], Graedel et al. [2012], Helbig et al. [2017], Lapko et al. [2016], Slowinski et al. [2013], The World Bank [2016], Ziemann et al. [2013], |
| **Purchasing flexibility** | Kraljic [1983]  
  *Make-or-buy opportunities: Porter [1979].  
  Substitution possibilities: European Commission [2014], Graedel et al. [2012], Slowinski et al. [2013]  
  Storage Risk: Cousins et al. [2008], Crocker et al. [2011], Skerlic et al. [2016]* |
| **Sustainability**      |                             |
| Environmental protection | Chen et al. [2014], Cousins et al. [2008], European Commission [2014], Gemechu et al. [2015], Graedel et al. [2012], Helbig et al. [2017], Reuter [2016], Rigot-Muller et al. [2013], Zhang et al. [2014]  |
| Social risk            | Bai and Sarkis [2014], Chen et al. [2014], European Commission [2014], Graedel et al. [2012]  
  *Living standards and work environment: Reuter [2016]* |
The theoretical reference is based on the revised literature. It is specifically chosen according to the applicability for lithium-ion battery manufacturers and includes profit impact, supply risk and sustainability considerations. The material classification reference can thereafter be applied in order to assess the criticality of different materials. This is followed by an investigation regarding how these material factors influence the purchasing environment and inbound supply chain sustainability for lithium-ion battery manufacturers, which is more thoroughly presented in the following chapters.

2.3. Profit Impact

A material’s profit impact is an indicator used to determine how much economic influence the material has on the business. Kraljic [1983] suggests a definition in terms of the volume purchased, the percentage of total purchase cost, and the material’s impact on product quality or business growth. Other researchers [Graedel et al. 2012; Slowinski et al. 2013] that focus on classification of critical metals, also include perspectives regarding price increase and volatility. The theoretical reference that is developed in this research incorporate these two studies. Profit impact is based on the material’s percentage of total cost including the sensitivity or probability to price fluctuations and increase over time, as well as its strategic importance for business growth or product quality.

2.3.1. Percentage of Total Cost

The material’s contribution of total purchasing cost becomes an important factor of consideration when assessing a material’s criticality, which can be determined through the two parameters; purchased volume and material price. Consequently Kraljic [1983] only brings up the purchased volume and the percentage of total cost as important components for the profit impact. In a similar way, the European Commission [2014] uses the gross value added to the GDP when measuring the economic importance of a material. This measurement is what other studies instead have used on a smaller scale for the corporate level to determine the material’s importance for the company. In excess of the percentage of total cost, Graedel et al. [2012] and Slowinski et al. [2013] note the importance of also determining the percentage of revenue impacted by the material, thus determining the other part for the profit impact.

In a market with volatile prices or material price increases over time, the material’s percentage of total cost may vary noteworthy. It is therefore important to reevaluate the classification of materials and the purchasing strategies continuously. The ability to pass through cost increases as a result of increased material prices have impact on the profit [Graedel et al. 2012; Slowinski et al. 2013]. Prices are in turn an outcome of the available demand and supply, which fosters the relative supplier and buyer powers as a result [Porter 1979]. Hence, price spikes may occur as a consequence of increased demand from new applications that outstrips the supply or as a consequence of supply uncertainties. In a case with high supplier power, the suppliers can respond to price falls by slashing production,
thus reducing the supply, in an effort to stem price erosion [Slowinski et al. 2013].

In a study of the criticality for metals, Graedel et al. [2012] also include the companion metal fraction in the economic component for the material price. When the metal is recovered as a trace constituent of a host metal rather than being mined principally by itself, the price is not only dependent on the demand for the metal but also dependent on the demand for the host metal. This is also grounded on whether it is technologically feasible to obtain the material and whether it is economically practical to do so [Graedel et al. 2012]. Additionally, governmental regulations also impact supply and demand, and hence the material prices as well [Slowinski et al. 2013]. The Bullwhip-Effect is described by Slowinski et al. [2013] as a reason for price fluctuations. In their study, they have noted that as an increased order volume moves from tier to tier in the supply chain, it can rapidly overdrive the price and supply dynamics, leading to fluctuations not only in price but also in material availability.

### 2.3.2. Business Importance

Assessment of business importance can assist in determining the significance of the specific material for the company. Kraljic [1983] defines the strategic importance by the two factors; product quality or influence on business growth. Various materials can hence influence the continued growth for a business by various degrees, if a material with high impact on the product quality is exposed to supply disruptions it can enforce production hold-ups or reduce quality on the final product. The materials importance for the corporate strategy is contributing to the profit impact and hence also the vulnerability to supply restrictions [Graedel et al. 2012]. In the same way, does the European Commission [2014] uses economic importance together with the supply risk to determine a material’s criticality. As described above, they focus on the material’s economic impact for the GDP, which can be compared with what Kraljic [1983] defines as the influence on business growth. Additionally, Lapko et al. [2016] stress that critical materials have a high importance and potential impact on the business.

### 2.4. Supply Risk

A material’s supply risk indicates the probability and vulnerability of disruptions in supply chain. The importance of a reliable supply is central for production companies as they cannot operate infallible without a trustworthy supply. Constraints in supply may lead to material shortage, as well as price increase or volatility, hence making material either unavailable or not affordable [Lapko et al. 2016]. In a similar way as the profit impact, the supply risk differs with the time scale, hence requiring continuously assessment of the material classification [Graedel et al. 2012]. This section covers the identified classification factors that affect supply risk, and it is specifically framed to be applicable to the lithium-ion battery manufacturing industry.
2.4.1. Material Availability

The material availability is primarily dependent on the source of the specific material, but can also be affected by limited natural resources, geological unavailability or political interventions. The concern for material availability is a strategical issue for companies to consider [Slowinski et al. 2013] and the importance of material availability is obvious to upstream firms [Alonso et al. 2007]. In order to regulate the input of materials in an efficient manner, it is necessary to know the availability of the materials and the suppliers [Crocker et al. 2011].

The vulnerability of the inbound supply chain with respect to access of available sources is highly dependent on the geographical location and existing physical implications of the source. Weather conditions may affect overseas deliveries or remote sourcing from countries that experience extreme weather, which may affect onshore operations in mines [Beer 2015]. Among the physical constraints, Alonso et al. [2007] also include the amount and quality of a resource that is physically determined and ultimately limits the resource availability. Furthermore, Craighead et al. [2007] found that severe disruptions in supply are more likely with geographical concentrations of suppliers. In excess of that, the geographical distance between activities in the supply chain is affecting the supply risk, also influencing the environmental impact with respect to available transport modes and delivery frequency.

The material availability is further determined by the possibilities for recycling that compounds the total supply of material from both primary and secondary (i.e. recycled) sources [Graedel et al. 2012]. Alonso et al. [2007] mean that the resource flow should be treated as a network driven by the demand for applications that use the material and moderated by the availability of substitutes and recycling. Hence, the possibilities for recycling also address the degree to which the availability of a material might be constrained.

2.4.2. Supply Market Structure

A useful relative indicator for the supply risk is the contemporary balance between supply and demand for the material in question [Graedel et al. 2012]. The number of suppliers and the competitiveness of the demand make up the supply market and influence the associated risk. Depending on the number of capable suppliers, the characteristics of the supply market is set and affects the bargaining power for suppliers and buyers [Porter 1979]. Shifts in supply or demand patterns can alter a material’s strategic category [Kraljic 1983]. Furthermore, it is concluded that a material’s criticality because of a mismatch in supply and demand creates an uncertain business environment and threatens the continuity of production operations [Graedel et al. 2012; Lapko et al. 2016; Slowinski et al. 2013].

The number of suppliers represented on the supply market, makes out the ground for supplier selection and a strategic fit is necessary to make the supply chain effective, efficient, and sustainable [Beer 2015].
A supplier that builds a strong relationship with customers, other suppliers, government, carriers and port operators, brings a higher level of security than other suppliers. Through information sharing and integration of decision processes, the supply chain performance relative to security can additionally be improved [Meixell and Norbis 2011]. Besides the number of available suppliers, the number of buyers on the market affects the supply risk and enforce higher supplier power when there is a high competitive demand. The buying power relative to other companies is yet another factor mentioned in the literature related to increased supply risk. Beer [2015] states that the supplier’s material allocation decisions between its customers is the most common reason to why the case companies in his study experienced irregularities in supply. Related to the supply market structure, Weele [2010] also considers the cost of changing supplier as an additional factor affecting the supply risk.

The supply market for many materials is not only dependent on one single industry, but also on the demand in other industries that are using the same material [Alonso et al. 2007]. More specifically for the materials that are being mined as companion of a host metal, the supply risk depends not only on the extent they are being mined but also on the magnitude of the host metal [Graedel et al. 2012]. Many materials are by-products from the refining of other materials, and if the demand for the co-produced material rises but demand for the primary element does not, supply restraints often result [Slowinski et al. 2013].

2.4.3. Geopolitical Supply Risk

Several studies highlight the constraints in supply due to governmental interventions and geopolitical factors [Beer 2015; Gemechu et al. 2015; Helbig et al. 2017; Lapko et al. 2016]. The political instability can be derived from the Worldwide Governance Indicators (WGI) of The World Bank [2016]. The assessment encompasses national, social, economic, and political factors that are associated with underlying vulnerability and economic distress. The European Commission [2014] uses the WGI as part of their assessment for supply risk, and Gemechu et al. [2015] conclude that the geopolitical-related supply risk indicators can play a vital role in managing the supply chain of critical resources as it highlights potential supply constraints. Furthermore, they also recommend that the factors should be included in the short-term decision-making, i.e. less than 10 years, as geopolitical risk may change over time as the circumstances and trade patterns shift.

Governmental policies, actions, and stability, significantly affect a company’s ability to obtain the material [Graedel et al. 2012]. In a recent study by Helbig et al. [2017], the country’s political risk and stability are identified as some of the key factors that can indicate the supply risk for materials. Ziemann et al. [2013] note that a change in political stability for the producing countries or raw material demand easily can affect the criticality of certain raw materials. Geographical concentration of sources may also increase the supply risk associated with the political situation in the same way as for the material availability [Slowinski et al. 2013].
Natural resources located in geographical areas with political instability and governmental interventions are exposed to a high risk regarding delays in supply. This is studied by Beer [2015], who finds that the case companies included in his research states that strikes in mines located in South America and Australia appear on a regular basis, causing disturbing delays for supply. Hence, being aware of political and governmental interventions have operational, as well as the strategic importance for companies that are depending on materials with supply chains through countries with high geopolitical-related supply risk.

2.4.4. Purchasing Flexibility

The purchasing flexibility indicates whether the purchasing company can be internally flexible when it comes to securing the supply of critical materials. It is grouped into two sections; make-or-buy opportunities and storage risk, those are further elaborated upon below.

Make-or-Buy Opportunities

The possibilities to make the material in-house reduce the supply risk and dependence of the supplier. Therefore, vertical integration in different parts of the supply chain may mitigate the related supply risk by opening up for possibilities to purchase materials further upstream. It is important for the company to determine the best balance between cost and flexibility, when looking for possibilities to purchase more upstream. In a case when the company is able to supply a large percentage of its supplies from owned sources they gain bargaining power and increase their competitiveness in long-term considerations [Kraljic 1983]. Porter [1979] also emphasizes this when he suggests that buyers increase their power over suppliers when they pose a credible threat of integrating backward to make the product themselves.

The make-or-buy opportunities are also closely related to the possibilities for material substitution. Vertical integration offers a company the chance of purchasing a material in a different step of the supply chain and opens up for other purchasing options of the materials, whereas the option for substitutability offers the company to purchase another material instead. Graedel et al. [2012] note that it is important to evaluate the degree of substitutability of the material in question when assessing the supply risk. The substitutability ability is comprised of three elements; substitute performance, environmental impact ratio, and the price ratio and the interplay yields the indicated supply risk [European Commission 2014]. Additionally, substitute ability requires extensive research, or several tests upon how existing possible substitutes impact the product quality [Slowinski et al. 2013].

Storage Risk

The consequences for a potential supply disruption may be reduced to some extent by keeping material in storage. The material’s storage possibilities can be expressed in terms of two sub-criteria. Firstly,
to what extent the material affects the organization’s capital accumulation. Secondly, the storage limitations related to demanded resources or equipment suitable to ensure the desired material’s technical attributes, volume and space. Inventory management highly affects the inbound supply chain for a company in terms of supply risk, storage capacity and cost. This needs to be thoroughly considered when planning the purchasing volume. Most organizations have some material storage due to economic benefits of buying large quantities that compensate for the cost of storage. Reasons for that are related to delivery which cannot exactly match the daily usage, or to guard against risk [Crocker et al. 2011].

Keeping material in storage is a way to reduce the supply risk, however there exist related consequences that need to addressed as a result of doing it. The inventory management concerns different departments within a company, which also adds a complexity to the purchasing process. The purchasing department usually focuses on purchasing large quantities with short payment terms, as it is the easiest way to obtain quantity discounts and also reduces the supply risk [Crocker et al. 2011; Skerlic et al. 2016]. However, large stock quantities are a problem for the logistics and financial departments as they can lead to deterioration of liquidity and increase the burden on the storage capacities [Skerlic et al. 2016]. Therefore, Cousins et al. [2008] and Crocker et al. [2011] recommend that the given quantity discounts should be held against the cost of holding additional inventory, depreciation of inventory, and reduced flexibility since they all consolidate and affect the company’s overall performance.

2.5. Sustainability

Sustainability is a third dimension that is suggested to complement the two dimensions in the Kraljic matrix and serve as a concern for purchasing decisions by several authors [Cousins et al. 2008; Pagell et al. 2010]. It is necessary to have management practices that do not only promote overall supply chain performance, but also focus on sustainability concerns from economic, environmental, and social perspectives [Govindan et al. 2014; Zhang et al. 2014]. The idea is based on the recognized definition for sustainable development by the Brundtland Commission [1987] that builds upon three main pillars; economic growth, environmental protection, and social risks.

The economic perspective serves to highlight the need for long-term financial performance for organizations while using its resources efficiently and responsibly. It is crucial to obtain an integrated economic perspective in the purchasing activities besides focusing on short-term financial results. The two dimensions of profit impact and supply risk presented by Kraljic [1983], that was presented above, influence the economic growth of the organization. Therefore, the sustainability dimension presented in this theoretical reference is focused on the two other main pillars; environmental protection and social risk. The theoretical reference is built on the definition made by Chen et al. [2014] and presented in Figure 2.2.
2.5.1. Environmental Protection

The environmental perspective highlights the need for environmental protection and to ensure that the consumption of natural resources, energy fuels and other materials hold a sustainable rate. Chen et al. [2014] divide the environmental sustainability factors into three different categories. Firstly, ecosystem vitality includes parameters related to the ecosystem such as air pollution, water quality, and contribution to climate change. Secondly, environmental health covers parameters affecting humans from a health perspective. Finally, environmental factors within production processes include parameters such as material use, energy consumption, renewable resources, waste disposal, and recycling of material.

The environmental degradation is becoming an important concern for manufacturing companies [Chen et al. 2014]. A commonly used model to determine the environmental impacts throughout the entire life cycle of a product is the concept of Life Cycle Assessment (LCA) [Zhang et al. 2014]. The concept covers all including activities such as the material acquisition, production, distribution, use, and disposal. Furthermore, Gemechu et al. [2015] suggest parameters such as global warming potential, metal depletion potential, human toxicity, and freshwater eco-toxicity as determining factors for the environmental life cycle impact assessment. A company’s sustainability considerations need to cover the full vertical supply chain and include the entire supply network, raising the need for a clear understanding of each stakeholder’s perspective and priorities [Chen et al. 2014; Cousins et al. 2008]. A challenge that is highlighted in literature is how to encourage suppliers into improving their environmental performance at every stage in the supply chain. In this process, Cousins et al. [2008]
list the key areas to address such as quality requirements, internal processing of materials including scrap, inventory, and transport requirements. They also raise the consideration for the environmental impact of packaging and the trade-off for eliminating transport packaging, which as a result can causes more damages or breakages to goods in transit. Another metric for environmental protection is the measurement of greenhouse gas emissions associated with raw material production, energy consumption, and transportation [Zhang et al. 2014].

The European Commission [2014] concludes that the improvement of environmental performance is closely linked to the raw materials. Furthermore, Graedel et al. [2012] found that metals in general, have a significant environmental impact as a result of the energy and water use in processing, or due to large emissions to air, water, and land. When analyzing the emissions for a material, attention also needs to be given to the geographic locations of the activities in the supply chain as well as to the transportation mode [Rigot-Muller et al. 2013]. Therefore, a holistic approach with concerns to long-term sustainability and forecasting criteria for raw material supply and production need to be included in the purchasing perspective early on in a product’s or a company’s life cycle [Helbig et al. 2017; Reuter 2016].

Good recycling possibilities of a material contribute to a better environmental performance and also improve the availability of material. On the other hand, issues such as sustainable extraction rates, the environmental regulation of mining, and land use competition may add constraints to the availability of materials [Graedel et al. 2012]. In line with that, Cousins et al. [2008] point out the need for a company policy that focuses on the environmental soundness with requirements for handling recycled products and disposals to increase the environmental performance.

2.5.2. Social Risks

The social aspects of sustainability is harder to define than the environmental impact because of intangible measures affected by cultural differences and divergent political governance [Bai and Sarkis 2014]. However, in similarity with the environmental protection Chen et al. [2014] also study factors for the social risks and defines them based on four parameters. Firstly, governance, which is assessed through the political stability, corruption, and trade barriers. Secondly, the country’s general education level. Thirdly, individual factors such as civil liberties and human rights. Fourth and finally, the community, which includes safety, cohesion, equity, and local technology as determining factors.

Statistical data on country level can be used to globally compare sustainability aspects between countries [Chen et al. 2014]. For example can poor governance be indicated by the World Governance Indicators (WGI) that include several measurements such as political stability, government effectiveness, rule of law, and control of corruption [European Commission 2014; The World Bank 2016]. Additionally, Reuter [2016] uses the Human Development Index (HDI) that measures factors like liv-
ing standards and knowledge, in order to indicate disadvantageous living conditions between countries. However, there exist a complexity with the metric accuracy and a critical aspect of sustainability measurement systems is the identification of key performance indicators [Bai and Sarkis 2014]. Therefore, the assessment of the social risks should be used rather as a generic estimate of the social risks since these assessments do not thoroughly represent real-life circumstances [Reuter 2016].

Positive social impact is of high importance for a company, and by having good transparency regarding the social contributions it can strengthen the company’s image. Corporate social responsibility (CSR) as a concept has been growing in importance over the years and is a form of corporate self-regulation that is integrated with the business model. More practically this means taking responsibility for that the activities are operated in an ethical manner and to ensure the social well-being of an organization and its connecting community. Indicators for a socially unsustainable organization are problems such as bad ethics, lacking human rights, low public involvement, among others. Social aspects such as fair wages and work safety can be influenced through active engagement at the work cite, whereas other aspects such as good education and medical care require CSR projects [Reuter 2016]. For example, do the objections to mining often stem from the perception of negative environmental and socioeconomic effects on the surrounding communities and ecosystems [Graedel et al. 2012], which could be prevented through active engagement and CSR projects.

2.6. Supply Risk Mitigation Strategies

In order to deal with the supply risk related to the materials, there is a need to develop and implement supply risk mitigation strategies. Alonso et al. [2007] even stress that the material criticality only could be mitigated if addressed proactively. Whenever a manufacturer must purchase a volume of critical items competitively under complex situations, supply management and purchasing strategies are becoming extremely important [Kraljic 1983]. The risk mitigation strategies reviewed in this study build upon the mitigation strategies presented by Lapko et al. [2016] for critical materials. They are additionally reviewed in comparison to other research projects within the field of risk mitigation strategies for critical materials. The vulnerability of supply restrictions differs with the organizational level and is different depending on whether you look at a global, national, or corporate level [Graedel et al. 2012]. The theoretical reference in this study is presented according to internal strategies focusing on the corporate level and external strategies focusing on the national and global level.

2.6.1. Internal Risk Mitigation Strategies

The internal risk mitigation strategies are focused on what the company can do internally in order to reduce the supply risk for the critical materials. These alternatives include various strategies with different aims and are presented according to the following main strategies:

- Diversification of suppliers (including multiple-sourcing) to hedge the risk
• Long-term contracts and price agreements to increase the control of unpredictable disruptions
• Vertical integration to increase the control of supply
• Material criticality assessment to avoid the risk
• Stockpiling material for speculation
• Postponement or new-development (including substitution) to increase the flexibility

Diversification of suppliers is a strategy that aims to hedge the supply risk. Erdmann and Graedel [2011] conclude that a shift in the supply base is a possible action to reduce criticality for a specific material. Beer [2015] identifies dual or multiple sourcing as the most important prevention for bottlenecks in supply in his case study. An option to diversify the suppliers is to approve multiple sources for supply of the material to reduce its risk. This can also be done by shifting the suppliers from countries with high supply risk as a consequence of weather, geopolitical risks, or sustainability issues to low-risk countries [Lapko et al. 2016]. Taking this into consideration would reduce dependency on sources in certain parts of the world that may occasionally be subject to extreme climate or political instabilities. Craighead et al. [2007] identify that when there is a high geographical concentration of the suppliers, it is favourable to work towards a globally dispersed portfolio in order to reduce the increased risk.

By applying long-term agreements and contracts with suppliers, the risk of supply disruptions can be controlled to a wider extent. Lapko et al. [2016] find that several of the companies in their study applied long-term contracts with suppliers and that most attention was paid to building long-term relationships, partnerships, and alliances with both suppliers and customers. Long-term agreements can increase the collaboration between organizations and by information sharing, potential hold-ups could be anticipated. Kraljic [1983] points out that in the short term, for strategic items where the supplier’s strength outweighs the company’s, the company should consolidate its supply position by concentrating fragmented purchased volumes in a single supplier. This means accepting high prices, and covering the full volume requirements through supply contracts. Supply agreements can be made with a fixed price for the medium or long-term. The product price could be linked to the material’s cost and therefore pass the material’s criticality on to the customers [Lapko et al. 2016].

To reduce the long-term risk of dependence on an unreliable source, the company should search for alternative suppliers or materials and also to consider backward integration to permit in-house production. Vertical integration is another option to further increase the control of the supply chain and reduce its supply risk. Lapko et al. [2016] conclude that supply chain and cross-industry joint venture, integration, or collaborations mitigate the risk associated with critical materials. On the other hand, if the company is stronger than the suppliers, it can spread volume over several suppliers, exploit price advantages, increase spot purchases, and reduce inventory levels [Kraljic 1983].
Material criticality assessment is one way for the organization to avoid the supply risk. This strategy aims to assess the criticality related to the material and hence open up for substitution possibility and auditing or termination of contracts [Lapko et al. 2016]. Kraljic [1983] highlights the need for a company to support their supply decisions of strategic items with a large amount of analytic techniques including market analysis, risk analysis, computer simulation, optimization models, price forecasting, and various other kinds of microeconomic analyses. And in a similar way, Alonso et al. [2007] suggest that companies who use critical materials need sophisticated methods that comprehend the many interrelated dynamics of supply, demand and substitution to prepare for possible future problems. When Slowinski et al. [2013] studied methods for assessing the risk of material shortage, they concluded that it is necessary to understand both the risk and the ability to mitigate it.

Stockpiling of materials is a speculation strategy that aims to anticipate future demand [Lapko et al. 2016]. Erdmann and Graedel [2011] define stockpiling as a risk mitigation strategy for price, along with insurances and/or antitrust actions. Besides speculation, stockpiling also improve the control and consequently reduce the risk. The last reviewed strategy for internal assessment is the choice of postponement where the aim is to delay the commitment of resources to maintain flexibility in the organization [Lapko et al. 2016]. Beyond the previously presented strategies, Lapko et al. [2016] also present innovation and new development as a risk mitigation strategy. It includes new technology development or increased efficiency that could reduce the dependence of critical materials. New development can also lead to that materials can be substituted, which in line with postponement adds flexibility for the company [Alonso et al. 2007]. Additionally, it can also result in an increase of a product’s lifetime and hence reduce the dependence of critical materials [Lapko et al. 2016].

2.6.2. External Risk Mitigation Strategies

The external strategies primarily include the entire industry with other potentially linked industries. However they can be impacted by the company itself by establishing additional incentives and assisting activities, in order to drive the development forward. These strategies are represented by:

- Recycling to increase the flexibility and control of material supply
- Established transparency to increase the security
- Exploration of new sources
- Development of sustainability standards

Recycling is a strategy that is on the borderline to being classified as an internal or an external strategy. Activities include the way the company reduce, reuse and recycle the including materials [Slowinski et al. 2013]. Recycling adds flexibility to the company by offering two various sources; either primary resources or through recycled material [Alonso et al. 2007]. In excess of that, Lapko et al. [2016] conclude that material criticality is a complex phenomenon caused by the interplay of different
actors, and that a single company cannot completely mitigate the risk by itself. They conclude that governmental interventions might be required to provide support and incentives for strategies, which are regarded as irrelevant or challenging at a company level but are important at an industry level. Eco-efficient and end-of-life product collection and recovery system are strategies that contribute to the use of materials in a more sustainable way [Erdmann and Graedel 2011]. This can include actions to improve the recycling technologies or the product design for recycling. The LCA, previously presented, is analyzing the entire supply chain, including the recycling possibilities. This way of closing the supply chain loop is also used for obtaining environmental performance.

Increased transparency adds security and visibility of the different material flows in the material value chain. Slowinski et al. [2013] stress that even after firms have undertaken a rigorous process for identifying materials of concern, the efforts to mitigate the supply chain risk may be hampered by a lack of transparency along the supply chain. Information exchange and data sharing between countries and international collaborations add traceability along the supply chain [Lapko et al. 2016] and contribute to increased performance.

On the global level, companies can engage in the exploration of new resources as a risk mitigation strategy, this includes geological research for potential new primary resources. Concentration in one country or one geographical area is a concern for a variety of geopolitical, environmental, and logistical reasons [Craighead et al. 2007; Slowinski et al. 2013]. Exploration projects for mining of metals can become an option in geographical areas with lower supply risk for the company. New exploration projects change the economic and technological conditions for the material, but what needs to be considered in mining is also the quality of the resources and to what extent the extraction requires prohibitively large energy, capital, environmental, and land costs if located in areas that are hard to access [Alonso et al. 2007].

Furthermore, sustainability standards can be developed on either an industry level or a global level as a way to mitigate the risk for critical materials. That includes a common certification and labeling system and international diplomacy to increase the transparency and evaluation of material’s supply chains. In excess of that, consumer education and awareness programs can be developed as a way to reduce the associated risks [Lapko et al. 2016].

2.7. Summary of Literature Review

This chapter presents the reviewed literature upon the topic of purchasing of critical material. Earlier research within the field of material classification and supply risk mitigation strategies are highlighted and presented. Based on the conducted literature, a theoretical reference is developed, which may work as an indicator for what aspects that need to be taken into consideration in the purchasing process of
the critical material for lithium-ion battery manufacturers. The theoretical reference includes profit impact, supply risk, sustainability factors and risk mitigation strategies. They are presented in Table 2.2, 2.3, 2.4 and 2.5.

Table 2.2.: Theoretical reference for material classification based on profit impact.

<table>
<thead>
<tr>
<th>Profit Impact</th>
<th>Factors of consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of Total Cost</td>
<td>The percentage of total cost is influenced by the material price and purchased quantity. Price fluctuations and increases are factors to take into consideration.</td>
</tr>
<tr>
<td>Business Importance</td>
<td>Materials with high impact on the product quality are important to secure from an economical long-term perspective.</td>
</tr>
</tbody>
</table>

Table 2.3.: Theoretical reference for material classification based on supply risk.

<table>
<thead>
<tr>
<th>Supply Risk</th>
<th>Factors of consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Availability</td>
<td>Is affected by limited natural resources, geographical location of suppliers, and recycling possibilities. A high geographical concentration of suppliers increases the risk for supply disruptions due to vulnerability for physical conditions or political instability.</td>
</tr>
<tr>
<td>Supply Market Structure</td>
<td>The number of available suppliers and the competitiveness in demand influence the buying position and companies may be disfavored as a consequence of suppliers’ allocation decisions. Shifts in demand patterns can alter a material’s strategic categorization.</td>
</tr>
<tr>
<td>Geopolitical Supply Risk</td>
<td>Governmental policies, actions and stability significantly affect a company’s ability to obtain a material. Changes in political stability of producing countries can affect the material’s criticality.</td>
</tr>
<tr>
<td>Make-or-Buy Opportunities</td>
<td>The possibilities to manufacture or prepare the material in-house reduces the supply risk. Therefore, vertical integration in different parts of the supply chain may mitigate the supply risk.</td>
</tr>
<tr>
<td>Storage Risk</td>
<td>Supply risk might be reduced by keeping stock and increasing order volume. The cost of holding additional inventory is a trade-off to the supply risk and to be considered in purchasing since it affects capital accumulation and material handling.</td>
</tr>
</tbody>
</table>
Table 2.4.: Theoretical reference for material classification based on sustainability impact.

<table>
<thead>
<tr>
<th>Sustainability</th>
<th>Factors of consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Protection</td>
<td>The impact the material has on ecosystem vitality, environmental health, and factors within production. Material recovery possibilities can strengthen the environmental perspective.</td>
</tr>
<tr>
<td>Social risk</td>
<td>The impact the material has related to the sourcing countries. Can be measured in political stability, working conditions, human rights and governance. The degree of need for CSR activities vary depending on the location of the material source.</td>
</tr>
</tbody>
</table>

Table 2.5.: Theoretical reference for supply risk mitigation strategies.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Factors of consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>Diversification of suppliers and inclusion of multiple sources to <em>hedge</em>, stockpiling and holding inventory to <em>speculate</em>, establishing long-term contracts and agreements as well as implementing vertical integration to <em>control</em>, postponement and new development, including substitution for <em>flexibility</em>.</td>
</tr>
<tr>
<td>External</td>
<td>Recycling for <em>control</em> and <em>flexibility</em>, increasing transparency along the value chain for <em>security</em>, exploration of new sources and establishing new sustainability standards.</td>
</tr>
</tbody>
</table>
3. Research Methodology

This chapter presents the overall research methodology. It includes a description of the research design, data collection methods and how the data analysis was performed. The chapter additionally discusses the reliability, validity, and generalizability of the results conducted in the research, as well as evaluates the ethics of the methods used.

3.1. Research Design

This research aims to investigate how unique critical material characteristics affect the purchasing environment for lithium-ion battery manufacturers and can be considered to obtain a sustainable inbound supply chain. Following this aim, an exploratory research design was used in combination with an inductive research approach. This research approach was necessary due to the insufficient amount of existing literature and few previously performed studies within the context. The theoretical limitation within the field is a consequence of the battery industry’s rapid development, hence challenging the academia to follow. Furthermore, an exploratory research was appropriate in order to gain familiarity with all the aspects related to lithium-ion battery manufacturing and to formulate the research question accurately and precisely related to the problematization of critical material purchasing. The chosen approach means that theory was developed from the observation of empirical reality as described by Collis and Hussey [2014], and it allowed this study’s problematization, objective, and research question to be updated along the process as new insights were made.

The design of the research is built upon overlapping processes that continuously were developed and evaluated throughout the study. A various number of activities took place along the way, in order to ensure that the performed study, in the end, was able to answer the research question. The main activities included in this research are illustrated in Figure 3.1, together with arrows indicating how gathered knowledge has influenced different parts of the research. According to recommendations by Blomkvist and Hallin [2015], the empirical study was performed in parallel to reviewing existing research in the field. This approach was applied throughout the study and not only influenced the research design but also ensured that the phenomenon was investigated in the best way. Triangulation with multiple sources was used both for different methods of data collection and for data analysis, which according to Collis and Hussey [2014] also contributes to a broader and more complementary view of the research problem.
3.2. Literature Review

A primary activity in this research was to conduct and review relevant literature. This enables possible gaps in the existing research to be identified [Collis and Hussey 2014] and provided us with insights of what was already an acquaintance in the research field, and what areas that needed to be more thoroughly investigated. During the literature review, it was realized that very few studies had been performed within purchasing of critical material and sustainability related to lithium-ion batteries, hence the literature review was divided into two parts. One focusing on previous studies upon the topic of material classification and different purchasing environments, and one focusing on the specific technology for lithium-ion batteries and the including materials. Existing theories covering strategies for supply risk mitigation and achievement of inbound supply chain sustainability were also included in the first review. The two literature reviews were performed in parallel throughout this research, which allowed them to influence the content of each other and become truly applicable for our study. According to recommendations by Gill and Johnson [2010], the reviews incorporated the latest literature and covered the major issues within the field of study. Additionally, the relevant literature was organized in a spreadsheet based on subareas of interest to get a comprehensive overview, and it was continuously updated throughout the process.

The first literature review upon the topic of critical material purchasing was conducted in order to get acquaintance within the field of industrial engineering and management that this research focuses on. The gathered knowledge from the contextual study on the battery industry together with this purchasing assessment helped us distinguish what theory concepts that could be applicable to this research. The theoretical reference presented in Chapter 2, established a necessary ground for what the findings and analysis in Chapter 5 are based on, hence relating this research’s results to findings already made in previous studies. The reviewed literature was conducted from online databases such
as Scopus, Web of Science, and other sources that assured peer reviewed literature.

The second literature review supporting the technical study was conducted in order to establish a contextual knowledge about the battery manufacturing industry. It provided directions for the empirical research and the content for the following interviews. Activities included reviewing technical reports of lithium-ion battery cells and focused on particular battery components such as; cathode, anode, electrolyte, and separator to gain a technical understanding of the battery cell technology. The study led to an assessment of the including critical material per component and the specific material characteristics. The gathered insights are presented in Chapter 4. Due to limited previous research on the topic of material assessment for lithium-ion batteries, inputs were conducted from studies on similar industries such as the mining sector and the electric vehicle market. These inputs are not automatically applicable to the battery industry’s inbound supply chain but have served as a necessary additional theory source for the material assessment. Furthermore, the technical literature review enhanced our sensibility to the collected data and added richness and depth to our findings presented in Chapter 5.

3.3. Data Collection

Data was collected through interviews with multiple informants in order to gather the information needed to answer our research question. The purpose of the interviews was to gain further understanding of purchasing critical material in the lithium-ion battery manufacturing industry, which could support the results from the two literature reviews. The interviews varied from being unstructured to semi-structured depending on the purpose of the interview. Early on in the process, interviews were used as data collection method to develop a deep understanding of the problem in accordance with recommendations by Blomkvist and Hallin [2015]. Therefore, the type of interviews in the initial phase were more unstructured, in order to discover different dimensions of the problem. At this stage, focus was on the specific characteristics of the materials and their effect on the purchasing environment. Over the time as our knowledge deepened, the interviews were more semi-structured in order to see patterns and draw conclusions in our research. The purpose here was to further identify critical factors of consideration for the achievement of a sustainable inbound supply chain in battery manufacturing. Because of the new context for this research, it required an exploratory approach also for the interviews that built on previous empirical findings from earlier performed interviews. In order to still be able to ensure reliability, previous interviewees were yet again contacted if new important insights were made after their interview was performed, in order to provide them the chance to give their interpretation of the phenomenon.

During this research, 15 experts with different expertise were interviewed, which allowed us to encounter the phenomenon from different perspectives. The selection of informants was performed in
accordance with recommendations by Eisenhardt and Graebner [2007] who highlight the importance of including numerous and highly knowledgeable informants for data collection. The interviewed experts had both broad and deep knowledge within the field of study and were able to provide valid information that was used to address this study’s research question. The interviewed experts have various experience within battery technology, purchasing, environmental implications, supply chain management, or a combination of several different aspects. The informants were selected based on the criterion that they had experience within at least one of these areas related to the battery industry, experts with experience from several areas were prioritized along with the experts who had profound knowledge of the specific ternary cell chemistry that this study focuses on. These criteria were chosen based on the scope of this study and to ensure that the investigated phenomenon could be studied. Recommendations from recognized knowledgeable people also contributed in the informant selection process to find experts within the field of study.

The interviews’ duration varied between 30 minutes up to 1.5 hours. Depending on the experts professional background, technical questions for material specific requirements and characteristics was asked, as well as questions regarding the related purchasing environment and possibilities to obtain a sustainable inbound supply chain. Table 3.1 presents an overview of the performed interviews.

<table>
<thead>
<tr>
<th>Informant</th>
<th>Date</th>
<th>Position</th>
<th>Time</th>
<th>Type of interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert A</td>
<td>01.02.2017</td>
<td>Professor in Chemical Engineering</td>
<td>1 hour</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert B</td>
<td>03.02.2017</td>
<td>Supply Chain Manager</td>
<td>30 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Expert C</td>
<td>03.02.2017</td>
<td>Material Technology Expert</td>
<td>20 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Expert D</td>
<td>14.02.2017</td>
<td>Supply Chain Manager</td>
<td>30 min</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert E</td>
<td>15.02.2017</td>
<td>Supply Chain Manager</td>
<td>30 min</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert F</td>
<td>22.02.2017</td>
<td>Head of Production</td>
<td>30 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Expert G</td>
<td>22.02.2017</td>
<td>Environmental Manager</td>
<td>1 hour</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert H</td>
<td>22.02.2017</td>
<td>Purchasing Manager</td>
<td>1 hour</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert I</td>
<td>22.02.2017</td>
<td>Chief Executive Officer</td>
<td>30 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Expert J</td>
<td>22.02.2017</td>
<td>Product Development Manager</td>
<td>30 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Expert K</td>
<td>03.03.2017</td>
<td>Chief of Strategy and Technology</td>
<td>1.5 hour</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert L</td>
<td>23.03.2017</td>
<td>Managing Director</td>
<td>45 min</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert M</td>
<td>12.04.2017</td>
<td>Cell Design Director</td>
<td>1 hour</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert N</td>
<td>24.04.2017</td>
<td>Chief Operating Officer</td>
<td>1.5 hours</td>
<td>Semi-structured</td>
</tr>
<tr>
<td>Expert O</td>
<td>26.04.2017</td>
<td>Chief Executive Officer</td>
<td>30 min</td>
<td>Semi-structured</td>
</tr>
</tbody>
</table>

In addition to the performed expert interviews, three interviews were held with business practitioners primarily from the mining industry. The purpose for these was to ensure a comprehensive understanding of the research topic related to the including minerals and metals, which is of high importance for lithium-ion battery manufacturers. By including business practitioners that operate on several hierarchical levels and within different functional areas it was possible to gain a wide understanding of the
phenomenon, as well as limit the risk of bias. The selection criteria for the business practitioners was
primarily based on the recognized organizations’ competence and the different informants positions.
A summary of the interviews with business practitioners are presented in Table 3.2. Furthermore,
information was also gathered from a two-day seminar that focused on the future mine and mineral
industry in Scandinavia. The seminar primarily contributed to this research with insights related
to the critical material characteristics assessment, the supply market analysis for minerals, and the
related sustainability factors. Both the authors attended the seminar and all of the interviews, these
were recorded with consent from the interviewee in parallel to that notes were taken.

Table 3.2.: Performed interviews with business practitioners.

<table>
<thead>
<tr>
<th>Informant</th>
<th>Date</th>
<th>Position</th>
<th>Time</th>
<th>Type of Interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business Practitioner A</td>
<td>06.02.2017</td>
<td>Project Geologist</td>
<td>30 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Business Practitioner B</td>
<td>24.02.2017</td>
<td>Geologist</td>
<td>45 min</td>
<td>Unstructured</td>
</tr>
<tr>
<td>Business Practitioner C</td>
<td>24.02.2017</td>
<td>Geologist</td>
<td>45 min</td>
<td>Unstructured</td>
</tr>
</tbody>
</table>

In excess of the unstructured and semi-structured interviews, informal meetings were continuously held
once or twice per week with the supervisor at Northvolt. The structure of these informal meetings was
open with a certain topic area for each meeting. This allowed various approaches to take form during
different stages of the research process and assisted in specifying the problematization, objective, and
research question. The informal meetings were also used as a method to discover new insights and as
a source for triangulation to strengthen findings from the empirical research.

3.4. Data Analysis

The data analysis process was conducted in four different steps according to recommendations by
Collis and Hussey [2014] and can be described accordingly; comprehending, synthesizing, theorizing,
and recontextualizing. In the first step, we made sure to fully understand the context and topic from
the conducted inputs. This was done by reviewing literature supporting the information gathered
from the interviewed experts and business practitioners. It helped us to interpret the findings and be
able to identify the meaning of the new discoveries. Secondly, the data was synthesized into differ-
ent themes related to the purchasing environment of the including material in lithium-ion batteries.
Thirdly, the data themes were compared with alternative explanations supported by theory revised
in the conducted technical and purchasing literature review. This step gave the qualitative data a
structure and conditions for further interpretation. In the last and final step, recontextualizing, we
went through the data with a sense of generalization to determine to what extent the results that have
emerged from the study was applicable in other settings.

This research is primarily based on qualitative data, which according to Collis and Hussey [2014]
can be less precise and more influenced by the context. On the other hand, this highly descriptive
method opens up for possibilities to reveal how theories can be applied in particular cases [Eisenhardt and Graebner 2007]. In our exploratory research upon the relatively new context of lithium-ion battery manufacturing, which is analyzed in a unique perspective of purchasing critical materials for the achievement of a sustainable inbound supply chain, we believe this is an appropriate method to apply. Collis and Hussey [2014] stress the need for collecting background information and establishing a contextual framework when using qualitative data, and we have applied that in our research. Triangulation of multiple sources assisted in the analyzing process and analytic methods were used in a rigorous and systematic manner to compare the empirical data with our findings in the conducted literature studies. In accordance with recommendations by Eisenhardt [1991], the comparison of data from the literature review and the interviews assisted in elucidating whether the findings could be replicated. We found this particularly valuable due to the limited existing research and experience within the studied context.

The research question for this study is posed in a way to fulfill the objective and has been divided into three sub-research questions that are mutually exclusive and collectively exhaustive. These sub-research questions are in turn stated in a way in which they build upon each other. Sub-research question 1 was primarily analyzed with support of data from the technical study and complemented with inputs from expert interviews. This assessment resulted in a comprehensive bill of material, which was necessary in order to gain the needed knowledge regarding critical material characteristics. The composed bill of material was conducted on a very technical detailed cell level including material volume and price to support the analysis in Chapter 5, but is however intentionally left out in this report due to company sensitive information. Thereafter, sub-research question 2 derived from the results of sub-research question 1 and was heavily supported by the expert interviews and the literature review for the purchasing of critical material. A pattern-matching logic was used to identify how the different material characteristics influence the purchasing environment. Furthermore, sub-research question 3 is grounded in the performed analyses for the other two sub-research questions and mostly based on the conducted interviews as a consequence of limited previous literature within the area.

A challenge exist with theorizing the collected data since it always entails trade-offs between simplicity and complexity, originality and semblance, as well as specificity and generality [Van Maanen et al. 2007]. In order to deal with this kind of compromises and time constraints, we have limited the amount of collected and analyzed data in our research. For instance, not all the materials included in a battery cell are taken into consideration but only the most strategic critical ones, according to the definition in Chapter 1.4. Selecting and focusing the data to the most important aspects meant to also leave some of the observed data outside of the research, such as inputs unrelated to the scope of the study. This is supported by Miles and Huberman [1994] who conclude that reducing the data is one of three key activities in the qualitative data analysis, along with two other flows of activities represented by data displaying and drawing conclusions.
3.4.1. Reliability and Validity

This research is mainly based on qualitative data, which is associated with a lower degree of reliability and less precision than quantitative data. Gathering data from interviews may have decreased the study’s reliability, however, Collis and Hussey [2014] indicate that if the data is collected in a systematic and methodical manner it is still associated with a high degree of validity. To counter the challenge of obtaining reliability in this research, focus has been put into performing the interviews in a consistent way and to generate reliable data that can be cross-compared. The lack of previous studies within the research field and difficulties to explore existing case studies may have affected this research’s quality. This issue was partly assessed by also including inputs from other related markets such as the industry of mining and electric vehicles, in order to spread the different angles of inputs. The highly exploratory approach of this study has also limited the possibility to perform all the interviews in the same way or according to a set interview template, as new insights were gathered along the way and influenced the main topic for each specific interview. In order to assure reliability we have instead aimed to perform the interviews based on different main themes depending on the informant’s knowledge. These themes are presented in an interview guide in Appendix A. In cases where new insights arose along the way, some additional clarifications were made by giving the informants a chance to contribute with their perspective in a follow-up conversation or email.

Validity is reached when the literature review is focused on the specific problematization. This means that the data collection methods are suitable for the purpose and that the findings respond to the research questions [Blomkvist and Hallin 2015], as well as reflects the studied phenomenon [Collis and Hussey 2014]. We have throughout the process made sure to continuously reevaluate the studied problem and its related content when new insights were made, in order to ensure that we are studying the right thing and to add validity to the research. Additionally, we have asked ourselves whether the evidence and conclusions in our research can stand up to close scrutiny. As described above, the research design is based on general research on the topic of purchasing critical material that have been reviewed and applied to the lithium-ion battery manufacturing industry. Bridging these two aspects might affect the dependability of this study’s final result, but has been guard against by ensuring validity through confirmations from industry experts and business practitioners.

In a similar way, triangulation was also applied to the empirical findings from interviews by comparing them with reviewed theories in the literature study, which according to McCutcheon and Meredith [1993] and Voss et al. [2002] increases the research validity. The data that was generated from the informants might have been biased based on specific prejudices and preferences, which is a limitation with the chosen method. However, the qualitative and quantitative data presented in the findings chapter, are supported by literature and confirmed by multiple informants. Unstructured and semi-structured interviews also include a risk related to that questions can be misinterpreted, which generate a challenge to ensure validity. If any statement was unclear or suspected to be misinterpreted, we took the
chance to ask clarifying questions to make sure that we interpret the informant’s input correctly.

Furthermore, the selection of informants contributed to ensuring the validity of this study. As previously mentioned, careful selection of informants was done based on the knowledge of the themes in Appendix A. This enabled us to analyze the investigated phenomenon from a relevant perspective and to perform a realistic analysis. Existing literature upon the topic is very limited which is why we primarily focused resources on approaching experienced informants from the industry. These experts are spread out globally and have different experiences from the industry. The advantage of choosing multiple informants with both a broad and deep knowledge within the field of study allowed us to resolve discrepancies among the provided data. Finally, by basing our informant selection criteria also on recommendations from recognized knowledgeable people, the validity and reliability could be further strengthened.

3.4.2. Generalizability

The generalizability of this study depends on the extent to which the findings related to purchasing of critical materials in lithium-ion batteries can be stretched to other settings. Collis and Hussey [2014] highlight the need for capturing the interactions and characteristics of the studied phenomenon in order to be able to generalize the findings. The identified patterns, concepts, and theories that have been generated in this environment can be applied to other companies being challenged with purchasing material with high criticality. The assessment and material classification methods applied are not unique to the lithium-ion batter manufacturing industry and hence can assist in other purchasing environment with high complexity. However, the results for the different materials are heavily dependent on the specific battery cell chemistry and therefore have limited applicability to companies not being dependent on the same bill of material. Specific manufacturers, vendors, suppliers or other providers are not central in this report, but rather the challenges that are general for the industry and therefore somewhat applicable for all companies acting in the context. Additionally, other industries handling materials and advanced raw materials similar to the ones included in lithium-ion batteries can also benefit from this study for how purchasing can support a sustainable inbound supply chain.

Consideration to generalizability has also been taken into account for the selection of the interviewees. During the selection process, we have aimed to interview people that are highly knowledgeable within the field of study, but still have different roles and backgrounds. In order to increase the possibility to generalize our findings, we have actively searched for informants with a differentiated viewpoint on the phenomenon to see if they could provide us with new or different insights. As a part of this, business practitioners have been interviewed with the aim to give a general understanding of the market for the battery industry and the specific materials in this study.
3.4.3. Ethics

This research is conducted in collaboration with Northvolt AB and therefore respecting confidentiality and anonymity were of importance. According to the company’s guidelines, the obtained sensitive information that should not be publicly shared, such as the conducted bill of material, was handled with careful consideration. Some information is intentionally left out of the report, and when included, the data has been modified to some extent but still allowing representation of the same phenomenon.

All informants that were interviewed have been informed about the purpose of the study and when conducting primary data from different informants we always offered anonymity and confidentiality. None of the informants are in the report referred to by name, in order to respect the secrecy that might have been shared in the conducted interviews. We made sure that the interviewees felt comfortable when providing us with information and that it has not been exposed without their consent. Research ethics was also taken into consideration when conducting secondary data from published sources. The general guidelines from KTH were followed regarding plagiarism and research misconduct.
4. Lithium-ion Battery Manufacturing

This chapter presents a contextual study of the researched industry of large-scale lithium-ion battery manufacturing. Firstly, the fundamental battery cell technology and the including components are presented. Thereafter, the including critical direct materials are presented according to their unique characteristics and sustainability impact, both from an environmental and social perspective.

4.1. Cell Technology

A lithium-ion battery is a complex system that depends on the number of cells inside the battery pack and the specific properties of the cell [Patry et al. 2014]. The cell is a battery’s central part and where the electrochemical reactions take place. There exist several different formats of the cell, where cylindrical, pouch and prismatic formats are the most common ones, while this study refers to the cylindrical format when speaking about lithium-ion battery cells. The battery cells can be arranged in series or parallel combinations to create the required voltage and capacity, depending on the particular application’s needs. Figure 4.1 illustrates a cylindrical lithium-ion battery cell with its including parts, as well as the movement of ions in the battery cell. Similar to all cell formats is the composition of five main components; cathode, anode, electrolyte, separator, and a durable case [Canis 2013].

![Cylindrical lithium-ion battery cell with including components. Adapted from Hodgson Corporation [2017].](image)

During discharge the cell lets electrons pass from a negative electrode, called anode, to a positive electrode, called cathode, via a liquid electrolyte [Hocking et al. 2016]. Simultaneously, as the lithium ions travel from the anode to the cathode through a porous separator that is located in between, the electrons are moving through the current collectors and the external circuit to perform work externally
The selection of cell materials is of major importance since it needs to be adapted according to the desired cell performance and the battery’s end application. Depending on the specific material composition, battery cells are usually classified as either high energy or high power. Gulbinska [2014] highlights that the materials that must be properly selected to match the cell design are the active material in the anode and cathode, current collecting foils, conductive solvents, as well as binders. Remaining cell materials as electrolyte solutions and porous separators, also need careful consideration in material selection. Ziemann et al. [2013] highlight that the characteristics of the overall lithium-ion battery is close connected to the qualities of the contained materials.

Besides the importance that materials play due to impact on cell performance, materials also represent the largest share of total cell cost, hence increasing the importance for lithium-ion battery manufacturers. Direct material represent the largest share of total battery cell cost, ranging from 70-80 percent in automated production [Helou and Brodd 2012; Santhanagopalan et al. 2016]. The material cost is driven by four main components that altogether represent 75 percent of total cell material cost; cathode active material, separator, electrolyte and anode active material [Santhanagopalan et al. 2016]. The components are further described in the following sections.

4.1.1. Cathode

The cathode plays a key role in the battery cell since it determines the lithium-ion battery characteristics. There are different types of materials and chemistry compositions that can be included in the cathode, depending on the usage of the battery. For instance, key considerations for lithium-ion batteries in Electric Vehicle (EV) applications are safety and energy density, and therefore the most common cathode options are based on the chemistries; NMC - Nickel Manganese Cobalt, NCA - Nickel Cobalt Aluminum, and LFP - Lithium Iron Phosphate because of their material properties [Hocking et al. 2016]. The different choices of cathode chemistries highly influence the battery performance, production cost, life span, energy density, and safety. Furthermore, Santhanagopalan et al. [2016] highlight the cathode as the component with the highest contribution to the material cost, representing more than 30 percent.

In battery cells, nickel acts as the electrochemically active material. Manganese is included since it contributes to the safety and lowers the raw material cost in the cathode, due to noteworthy cheaper material price than nickel and cobalt [Gulbinska 2014]. It is important to keep nickel out of the lithium layer to enable lithium ions to unobstructed move through the cathode, which is the role of cobalt. Lithium is added to the active material during the manufacturing processes in the most critical production step, called the precursor [Gulbinska 2014]. Thereafter, the active material particles of nickel, manganese, cobalt and lithium, are held together with a polymeric binder, which in lithium-
ion batteries is usually polyvinylidene difluoride (PVDF). The mixture also consists of a solvent that simplifies the bonding of the active material and may in the cathode be n-methyl-2-pyrrolidone (NMP) [Li et al. 2010]. The mixture is placed on the metallic current collector, which in the cathode is made of aluminum foil.

- Component functioning: The cathode can be considered as the most important component as it decides the battery’s characteristics and highly influences the overall battery performance.

- Including material: Active material consists of lithium, nickel, cobalt, and manganese. Binder and solvent are PVDF and NMP respectively. The current collector consists of aluminum foil.

4.1.2. Anode

During discharge, the anode represents the negative electrode in lithium-ion batteries and helps to reverse the electrons in the circuit. It also adds stability to the battery cell and mitigates the possibility of thermal runaway [Li et al. 2010]. Graphite is generally used as the anode material because of favorable characteristics such as good material accessibility, relatively low price, and good charge capacity. The graphite layer that is coated on both sides of the anode many times consist of a mixture between natural and synthetic graphite in order to balance the strengths of each. Due to significantly lower cost than synthetic graphite, the preferred anode material, from a cost point of view, is natural graphite [Tarascon et al. 2011].

The active materials, consisting of natural and synthetic graphite, are held together with a polymeric binder and solvent [Gulbinska 2014]. For the anode these may be styrene-butadiene-rubber (SBR) as binder and carboxymethyl cellulose (CMC) as solvent. This aqueous system with SBR and CMC in the anode has less environmental hazard and is cheaper than the one used in the cathode [Li et al. 2010]. Furthermore, copper foil is serving as the anode’s current collector.

- Component functioning: The anode reverses the electrons in the circuit, add stability to the battery cell and mitigates the possibility of thermal runaway.

- Including material: Natural and synthetic graphite as the active material. Binder and solvent are SBR and CMC respectively. The current collector consists of copper foil.

4.1.3. Electrolyte

Lithium-ion batteries can be classified into two different types based on the type of electrolyte used; liquefied lithium ion battery (LIB) with liquid electrolyte, or polymer lithium ion battery (PLB) that contains either gel or solid electrolyte. The electrolyte serves as a catalyst and is called an activator since it enables and promotes the ion flow. The including chemicals are used in the solution since they exhibit a suitable conductivity for use in lithium-ion batteries [Li et al. 2010]. Futhermore, it is
considered as one of the core components in lithium-ion batteries and has a big impact on the battery cell’s lifetime. Having high-purity solvents in the preparation of electrolytes is a very important factor, where even low levels of water and/or alcohol tend to shorten the battery life [Henriksen et al. 2002], thus increasing the importance of having the right quality material, as well as correct treatment in the electrolyte manufacturing process.

The liquid electrolyte is made up of lithium salt compounds, such as lithium hexafluorophosphate (LiPF6), and organic solvents containing linear and cyclic carbonates, such as ethylene carbonate (EC), dimethyl carbonate (DMC) and ethyl methyl carbonate (EMC). The combination of linear and cyclic carbonates in the electrolyte contributes with high conductivity, as well as with the ability to form a reaction layer. The solvents included in the electrolyte are volatile and highly flammable with vapors that can be a safety issue for lithium-ion batteries [European Chemicals Agency 2017]. With a flashpoint at room temperature, they can cause fire or explosions when exposed to oxygen and an ignition source [Hess et al. 2015]. These are issues that need to be controlled in manufacturing, storing, and transportation [Aurbach et al. 2004], adding complexity to the material handling activities. Extensive efforts and research have been made to develop a well-functioning electrolyte, but it still exists a trade-off between its flammability and performance [Li et al. 2010].

- Component functioning: The electrolyte enables and promotes the ion flow between the cathode and the anode during charge and discharge.

- Including material: Organic solvents consists of ethylene carbonate (EC), dimethyl carbonate (DMC) and ethyl methyl carbonate (EMC) and lithium salt LiPF6.

4.1.4. Separator

The essential function of the separator is to prevent the cathode and anode from contacting each other while allowing lithium ions to flow in the cell. It is a porous membrane that is located between the cathode and anode. The separator affects the battery performance, the cell’s energy and power density, cycle life, and safety [Gulbinska 2014], hence quality is of high importance. Some characteristics that make a good separator is having high ionic flow, negligible electronic conductivity, good chemical stability towards the electrolyte, good wettability, sufficient physical strength in the assembly process, among others [Li et al. 2010]. The most common used separators for lithium-ion batteries are made of plastic compounds such as polypropylene (PP) and polyethylene (PEP), as these are chemically and electrochemically stable [Arora and Zhang 2004].

- Component functioning: The separator prevents the cathode and anode to contact each other, while allowing lithium ions to flow in the cell.

- Including material: Plastic compounds such as polypropylene (PP) and polyethylene (PEP).
4.2. Critical Direct Materials in Lithium-ion Batteries

In order to reduce costs of lithium-ion batteries, obtaining cheaper materials and more efficient material processing techniques are necessary [Gaines and Cuenca 2000; Li et al. 2010]. This study has grouped the critical material into clusters of minerals, metals and chemicals. These three clusters of materials are included in the battery components that represent the major importance for cell performance and cost. The minerals and metals are presented separately for each and every raw material because they experience high material uniqueness, and are likely to be purchased separately to be processed in-house. The chemicals on the other hand, are assessed component-wise as electrolyte and separator, since these are unlikely to be procured as raw material but rather dependent on a specific component manufacturer. The cluster of chemicals also covers the binder and solvents included in the cathode and anode, which are named as other chemicals.

Minerals refer to the material included in the electrodes’ active material and the metals refer to the current collectors that consist of manufactured metal foils. Common characteristics for these materials are that they are natural resources with limited availability and wide geographical spread, which can implicate supply and/or pricing [Canis 2013]. Figure 4.2 illustrates the five largest raw materials reserves in 2016 for the including minerals and metals.

![Figure 4.2: The world's five largest raw material reserves. Adapted with data from USGS [2017].](image)
4.2.1. Minerals

The minerals included in this assessment are cobalt, graphite, lithium, manganese and nickel. These are included in different formats in the battery cell, and require high quality with battery grade purity. Lithium-ion battery manufacturers are dependent on a combination of suitable suppliers offering the required battery format, refineries with sufficient capacity, and availability of raw material sources. The following section focuses mainly on the availability of the primary raw material source. The existing suppliers of the material format that the battery manufacturers demand is addressed to a lesser extent.

Cobalt

In most cases, cobalt is sourced as a byproduct when mining ores of nickel and copper. These respectively represent 55 and 35 percent of the total cobalt production, while the remaining 10 percent of the world production originates from primary cobalt operations [European Commission 2015b; USGS 2017]. The majority of the crude ores are located in the Democratic Republic of Congo, representing more than half of the world’s production, which is illustrated in Figure 4.3. During 2016, China was the leading producer of refined cobalt, and refining also takes place in other countries such as Finland [Schmidt et al. 2016]. However, the dependency on D.R. of Congo still exists since it is where the majority of the mines are located, which leads to a high dependency on a few critical sources and high environmental impact due to long transportation routes. As a matter of fact, about 980 g out of every 1 kg of refined cobalt chemical on a global average have been shipped a long distance prior to the battery manufacturing process [Schmidt et al. 2016]

![Cobalt Global Mine Production](image)

**Figure 4.3.** Global mine production of cobalt, the year 2016. Source: USGS [2017].

The usage of cobalt for lithium-ion battery manufacturers involves several disadvantages such as contribution towards material depletion, a considerable risk for supply shortage, and risks of negative social aspects along with its supply chain [Reuter 2016]. The European Commission [2014] has defined cobalt as a critical material because of its high economic importance and substantial supply risk. Due to its extensive mine production in the D.R. of Congo, it has furthermore also been highlighted as a potential conflict mineral [European Commission 2015b]. The definition of conflict minerals con-
siders natural resources that are traded after being extracted in a conflict zone and contributes to finance the violence [Langerman 2011].

Due to the advancing use of cobalt mainly in batteries, the demand is expected to increase over the next ten years. The European Commission [2014] has forecasted an annual demand growth of 6 percent to 2020, during the same time period they foresee a small surplus of supply. On the contrary, USGS [2017] forecasts a shift in the global cobalt market from surplus to deficit because of the demand growth for refined cobalt, as a result of increased battery production and aerospace industries. Substitutes for cobalt in these applications are continuously being sought as the metal is both rare and price-volatile [European Commission 2015b].

Cobalt is recycled both for economic and environmental reasons to lower costs coupled with cobalt extraction from ores and prevent damage on the environment caused by batteries [European Commission 2015b]. The end-of-life recycling rate for products that include cobalt is estimated to 68 percent, which is higher than for other metals [European Commission 2015b]. On the other hand, cobalt contained in purchased scrap represented only 30 percent of the cobalt consumption in 2016 [USGS 2017], which is lower than for most other metals [European Commission 2015b].

Graphite
Graphite can either be mined from natural resources or be synthesized from oil-based feedstocks. Natural graphite represents the majority of the anode market and is favorable due to its significantly lower cost compared to synthetic graphite [Yoshino 2014]. However, synthetic graphite has an important role when it comes to cell performance, and is therefore necessary to be included in the battery cell. The European Commission [2015b] points out that rising prices of natural graphite may lead to increasing substitution with synthetic graphite in future anode applications. The requirement on purity of anode graphite is high since presence of trace elements can have significant effects on the electrochemical properties [European Commission 2015b].

The global mine production of natural graphite in 2016 amounted to 1.2 million ton, which is presented in Figure 4.4. There is a clear concentration to a few countries that represent the majority of the graphite production. The two largest mine producers of graphite, China and India representing more than 80 percent of the total market, both have high political risk ratings that increase the supply risk substantially [European Commission 2015b]. The supply risk and high economic importance has led to that natural graphite has been categorized as critical material by the European Commission [2014], in conformity with cobalt.
At present, recycling of graphite from end-of-life products is very low due to the lack of economic incentives combined with technical challenges. The graphite materials in batteries are lost during the pyro-metallurgical process used for recycling, however, there are pilot studies on the recovering possibilities of graphite from batteries by using a hydro-metallurgical process instead [European Commission 2015b]. The increased production of batteries will contribute significantly to the total demand for natural graphite but the risk of resource depletion caused by battery manufacturing is limited due to large reserves even though recycling of natural graphite is limited [Reuter 2016].

**Lithium**

Lithium is well-suitable for battery applications since it is the lightest known metal with the greatest electrochemical potential, hence providing a high energy-to-weight ratio [Gulbinska 2014]. The material can be purchased in several formats but is included as lithium hydroxide in the cathode’s active material. Lithium carbonate and lithium hydroxide represent the largest markets, accounting for 50 and 20 percent respectively of global lithium sales in 2015. Furthermore, the sales of lithium hydroxide has increased since 2015 due to the increasing popularity of NMC and NCA battery chemistries. Intermediate lithium concentrates need to be further refined into higher purity lithium products before they can be used in battery manufacturing. For this cause, the lithium concentrates are transported to conversion plants that are primarily located in China. An experienced supply shortage last year, especially caused by China, led to a significant increase in pricing and the lithium price nearly doubled in six months during year 2016. [Hocking et al. 2016]

Numerous of reports and previous studies have discussed the topic of possible resource depletion of lithium due to the rapid development of electronic applications and batteries. However, Reuter [2016] concludes that the present economic reserves of lithium are sufficiently abundant to satisfy the expected material demand for production of lithium-ion batteries to the automotive industry. Chile, Bolivia, and Argentina are known as the Lithium Triangle and possess two-thirds of the world’s lithium reserves. Bolivia has the largest lithium brine resource, however, the deposit has a 19 to
1 magnesium:lithium ratio, making it uneconomic to exploit until the rise in lithium prices in 2016 [Hocking et al. 2016]. Figure 4.5 illustrates the global mine production in year 2016.

![Lithium - Global Mine Production](image)

**Figure 4.5.** Global mine production of lithium, the year 2016. Source: USGS [2017].

The increased lithium demand for battery applications is the driving force for the worldwide increase of lithium production [USGS 2017]. Since both the lithium reserve and production are controlled by a few countries, securing a sustainable supply is of high importance for concerned companies [Gemechu et al. 2015]. In line with that, USGS [2017] has seen a trend towards strategic alliances and joint ventures between technology companies and exploration companies to ensure a reliable, diversified supply of lithium for battery suppliers. Lithium is not identified as a critical mineral according to the European Commission [2014] but is very close to the threshold. The recycling of lithium has historically been insignificant but as the consumption of lithium batteries has increased, so has the recycling [USGS 2017].

**Manganese**

Manganese is an including material in lithium-ion batteries because of its good electrochemical behavior. In addition to lowering the cathode material costs [Gulbinska 2014], it also impacts the battery cell’s safety and thermal stability [Dahbi et al. 2011]. The usage of manganese in batteries is marginal but Ziemann et al. [2013] point out that the supply risk will change due to the increased electric mobility in the future and thus foster an increased demand of manganese for lithium-ion batteries. Factors like the lower material price and better material availability are believed to drive an increased demand of manganese in the near future as a substitute for the use of nickel and cobalt as major cathode material [Notter et al. 2010].

The global mine production of manganese is 16 million ton, the year 2016, with suppliers distributed over the globe as illustrated in Figure 4.6. The global manganese production is represented by nearly 60 percent in South Africa, China, and Australia [USGS 2017], thus indicating a good geographical spread of the available production sources. With respect to the identified manganese resources, about 75 percent are concentrated in South Africa [Ziemann et al. 2013].
There are some contradictory beliefs regarding the sustainability importance related to Manganese. Helbig et al. [2017] value the specific environmental implications for manganese as of minor importance because of high ore grades and low-hazard extraction technologies due to a relatively high abundance of manganese in the earth’s crust. On the other hand, Ziemann et al. [2013] conclude that manganese has a low reserve to production ratio and has a high cumulative energy demand, thus making it environmentally relevant. The manganese recycling is additionally inefficient and primary metal is always needed for manufacturing new products, which increases the dependency on primary manganese sources [Ziemann et al. 2013]. USGS [2017] finds the recovery of manganese in 2016 as negligible.

Nickel
Nickel is electrochemically stable over the voltage range of a battery and in addition it is relatively stable to oxidation, which is beneficial in the manufacturing process [Gulbinska 2014]. Nickel is the fifth most common element found on earth, but the reserves that could be economically mined are limited. The global production of nickel is spread across the globe with no significant country dominating the market, which is illustrated in Figure 4.7. However, in the near future, the distribution might be changed as the nickel produced in the Philippines is expected to decline as a consequence of harder environmental demands in 2017 that suspended production at dozens of mines. [USGS 2017]
The worldwide usage of nickel has increased over time and is closely related to economic development. It is an available and relatively inexpensive material, but the price of nickel has shown considerable volatility over the last forty years. During late 2015 and early 2016, the prices were at historically low levels. Furthermore, the risk for resource depletion is also low since there exist a functioning recycling process for nickel. In 2016, the recovered nickel represented 43 percent of the nickel consumption and there is a clear distinction between the use of newly produced metal and recycled scrap. The newly produced nickel is mainly used in the production of stainless steel but also in batteries. [USGS 2017]

4.2.2. Metals

Metals are included in the assessment of critical direct materials in two different formats; aluminum foil as the cathode current collector and copper foil as the anode current collector. The metal foils are important for the battery cell’s functioning and require high quality and battery grade purity. Similar to the minerals, lithium-ion battery manufacturers are dependent on a combination of suppliers offering the demanded battery format, as well as the availability of primary sources. This section focus primarily on the availability of the raw material source of aluminum and copper.

Aluminum

Aluminum origin from bauxite ores and the global resources are estimated to be between 55 to 75 billion tons, which is forecasted to be sufficient to meet the world’s metal demand well into the future. Aluminum has a global production of 57.6 million ton, where China represents more than 50 percent of the total production, the remaining production breakdown is illustrated in Figure 4.8. Additionally, the world primary aluminum production slightly increased from 2015 to 2016, even though the price for aluminum was low. Aluminum has good recycling possibilities, with 31 percent of the consumption in 2016 represented by recovered aluminum from old scrap. [USGS 2017]

![Aluminum - Global Mine Production](image)

**Figure 4.8:** Global mine production of aluminum, the year 2016. Source: USGS [2017].
Copper

The global copper mine production is a lot more equally spread out over geographical locations than aluminum. Chile is the largest producer and the total mine production in 2016 was 19.4 million ton, which is illustrated in Figure 4.9. The projections for 2017 indicate that the global refined copper production will exceed the consumption by 1 percent or 160,000 ton. However, there exist recycling possibilities for copper. It is estimated that the amount of old scrap copper that is refined to metal and alloys is equivalent to 9 percent of appeared consumption. [USGS 2017]

An additional consideration for the metals included in lithium-ion batteries is the environmental impact they cause. The environmental impact exists due to high energy intensity and emissions for metal production and other associated activities related to the mining, extraction, and refining processes [Gemechu et al. 2015].

4.2.3. Chemicals

The third and final cluster of critical materials is the group of chemicals that exist in multiple components included in the lithium-ion battery cell. The separator and electrolyte are entire components already presented in Chapter 4.1, hence the following section focuses mainly on the remaining group of other chemicals, represented by the solvents and binders used both in the anode and cathode of lithium-ion batteries. The solvents assist electron conduction, while the binders assure adhesion to the current collectors [Gulbinska 2014].

The organic system of binder and solvent used for coating onto the current collector adds concerns about cost, environmental impact, and safety [Li et al. 2010]. Lisbona and Snee [2011] emphasize the hazards associated with lithium-ion battery cells. They conclude that safe storage, packaging and labeling practices, as well as the communication among parties, are essential factors to ensure safety across the battery’s lifecycle. The aqueous systems such as SBR and CMC used for the anode, pose less of an environmental hazard than NMP and PVDF. However, there exist a trade-off regarding
complexity in the manufacturing process related to need for removing the water, hence limiting the suitability of this option for the cathode application [Li et al. 2010].

4.3. Assessment of Material Sustainability

Lithium-ion battery manufacturing is a complex industry with existing skepticism related to environmental and social impacts that the operation is causing. Sustainability issues are especially necessary to consider as the battery manufacturers handle materials that may cause a negative environmental impact as well as may be sourced from countries with high social risk. This section assess the environmental and social issues related to the critical direct material included in the battery cell. The illustrative colors that are presented in Table 4.1 work as an indicator to what extent the material has a sustainability affect for lithium-ion battery manufacturers.

<table>
<thead>
<tr>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium-High</th>
<th>High</th>
</tr>
</thead>
</table>

Table 4.1.: Coloured ranking of environmental and social sustainability risk.

4.3.1. Environmental Impact

The environmental classification is performed based on the theoretical reference presented in Chapter 2 and covers the three environmental indicators presented by Chen et al. [2014]: ecosystem vitality, environmental health, and factors within production. The latter includes parameters such as material use, energy consumption, waste disposal, and recycling possibilities. This environmental assessment focuses on the recycling possibilities due to limited existing information for the other parameters. The assessment of the recycling possibilities for chemicals was not possible to perform since they are not mineral commodities and hence not included in the report by USGS [2017]. The classification made in this section is based with respect to the following three environmental criteria:

- **Ecosystem Vitality** - Indicates to what extent the material may impact land, water, and air quality as well as the materials contribution to climate change. The assessment is based on hazard classifications made by the European Chemicals Agency [2017].

- **Environmental Health** - Indicates to what extent the material may cause damage to human health. The assessment is based on hazard classifications made by the European Chemicals Agency [2017].

Table 4.2 presents the environmental impact assessment of the different minerals, metals, and chemicals. The total impact ranking in the column to the far right is a weighted value of the three environmental criteria. The weighted average is rounded up, hence this assessment can be considered as a conservative evaluation. A detailed presentation of each criterion is entailed in Appendix B.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ecosystem Vitality</th>
<th>Environmental Health</th>
<th>Recycling Possibilities</th>
<th>Total Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minerals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td></td>
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<tr>
<td>Graphite</td>
<td></td>
<td></td>
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<tr>
<td>Lithium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Aluminum</td>
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<td></td>
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<tr>
<td>Copper</td>
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<td></td>
</tr>
<tr>
<td>Chemicals</td>
<td>Electrolyte</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Separator</td>
<td></td>
<td>-</td>
<td></td>
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<tr>
<td></td>
<td>Other Chemicals</td>
<td></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

The cluster of minerals contributes to an environmental sustainability impact in all three of the assessed classifications, to some extent. Cobalt is protruding among the minerals, mainly because of its possible harmful effects on human health and the ecosystem [European Chemicals Agency 2017], however, there exist good recycling possibilities. The remaining minerals are all ranked with a weighted medium-low environmental classification. The negative environmental impact due limited possibilities for recycling of manganese and graphite is outweighed by their negligible effects on the ecosystem and environmental health. There exist a risk related to nickel and its impact on environmental health, however that does not noteworthy influence the overall environmental impact ranking. Additionally, Schmidt et al. [2016] highlight the environmental impact caused by the extraction and beneficiation of especially nickel and cobalt for the use in batteries. These are additional environmental concerns related to the minerals that should be taken into consideration by lithium-ion battery manufacturers.

Among the metals, the assessment of aluminum has resulted in an overall low ranking and copper in a medium-low ranking of the total environmental impact. The classification of ecosystem vitality is a risk for copper because of its toxicity to the aquatic life [European Chemicals Agency 2017]. What is additionally worth to consider in excess of the environmental impact classification illustrated in Table 4.2 is that the manufacturing process of copper and aluminum requires a large amount of energy associated to the mining, extraction and refining processes, resulting in a negative environmental impact.
Gemechu et al. [2015]. Notter et al. [2010] found that the supply of copper and aluminum is one of the major contributors to the environmental burden caused by the battery, which is necessary to take into consideration, however, not highlighted in the assessment in Table 4.2.

Among the chemicals, the electrolyte experiences the highest impact on the environmental health, mainly because the solvent EC and the lithium salt (LiPF6) may damage organs. Additionally, the remaining solvents included in the electrolyte, EMC and DMC, are highly flammable and therefore also considered as a danger to human health [European Chemicals Agency 2017]. However, since there is no risk for ecosystem vitality it results in an overall medium-low environmental ranking for the electrolyte. Among the group of other chemicals, it is only the NMP solvent that is toxic for human health, hence resulting in a medium-low ranking for that group of material. Finally, the separator experience no risk for either ecosystem or health, resulting in low overall ranking for environmental impact.

4.3.2. Social Impact

The social sustainability assessment is performed based on the theoretical reference presented in Chapter 2 and covers the social indicators presented by Chen et al. [2014]. The classification of educational level is intentionally left out due to limited accessible information. Instead, the social risk assessment includes political stability, working conditions, human rights and country governance, since these can be based on available measurements from trustworthy organizations. The social sustainability assessment gives an indication regarding to what extent the included critical materials have a negative impact on the surrounding social system. The classification is made upon the four different social indicators with respect to different countries of source:

- **Political Stability** - Measures the likelihood of political instability and politically motivated violence, including terrorism to occur. Based on country data in the Worldwide Governance Indicators (WGI) [The World Bank 2016].


- **Human Rights** - Measures the level of human development such as long and healthy life, being knowledgeable and have a decent standard of living. The Human Development Index (HDI) is a mean of the three dimensions and developed by the United Nations [2016].

- **Governance** - Measures the social risk that citizens face of tangible impact of corruption on a daily basis. The assessment is based on the Corruption Perception Index 2016, conducted by Transparency International [2017].
Table 4.3 presents the social impact assessment of the different minerals, metals, and chemicals. The total social impact ranking in the column to the far right is a weighted value of the four social criteria and the three countries with the largest shares of the source. The weighted average is rounded up, hence this assessment can be considered as a conservative evaluation. A detailed presentation of each criteria is entailed in Appendix B.

<table>
<thead>
<tr>
<th>Country of Source</th>
<th>Political Stability</th>
<th>Working Conditions</th>
<th>Human Rights</th>
<th>Country Governance</th>
<th>Total Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>D. R. of Congo</td>
<td>54%</td>
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<tr>
<td>China</td>
<td>6%</td>
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<tr>
<td>Canada</td>
<td>6%</td>
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<tr>
<td>Graphite</td>
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<tr>
<td>China</td>
<td>65%</td>
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<tr>
<td>India</td>
<td>14%</td>
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<tr>
<td>Brazil</td>
<td>7%</td>
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<tr>
<td>Lithium</td>
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<tr>
<td>Australia</td>
<td>41%</td>
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<tr>
<td>Chile</td>
<td>34%</td>
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<tr>
<td>Argentina</td>
<td>16%</td>
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<tr>
<td>Manganese</td>
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<tr>
<td>South Africa</td>
<td>29%</td>
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<tr>
<td>China</td>
<td>19%</td>
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<tr>
<td>Australia</td>
<td>16%</td>
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<tr>
<td>Nickel</td>
<td></td>
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<tr>
<td>Philippines</td>
<td>22%</td>
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<tr>
<td>Russia</td>
<td>12%</td>
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<tr>
<td>Canada</td>
<td>11%</td>
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<tr>
<td>Aluminum</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>China</td>
<td>54%</td>
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<tr>
<td>Russia</td>
<td>6%</td>
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<tr>
<td>Canada</td>
<td>6%</td>
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<tr>
<td>Copper</td>
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<tr>
<td>Chile</td>
<td>28%</td>
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<tr>
<td>Peru</td>
<td>12%</td>
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<tr>
<td>China</td>
<td>9%</td>
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<tr>
<td>Chemicals</td>
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<tr>
<td>Japan</td>
<td>-</td>
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<tr>
<td>United States</td>
<td>-</td>
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<tr>
<td>Germany</td>
<td>-</td>
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</tbody>
</table>
Cobalt and graphite are the two materials that are ranked with high social sustainability risk, indicated with the red colour in Table 4.3. This assessment is in line with the material criticality ranking made by the European Commission [2015b], which has classified both cobalt and graphite as critical materials. The reason for that is that the main country of source for cobalt is the D.R. of Congo and for natural graphite it is China, two countries performing poorly on the social risk assessment. The D.R. of Congo ranks on 176th of 188th place in the Human Development Index, and there exist particularly indicated risks associated with child and forced labor as well as insufficient wages. Reuter [2016] states that the cobalt production located in the D.R. of Congo implies a certain need for corporate activities and supplier management to ensure appropriate production conditions and improve general living conditions. What is worth to highlight in this assessment related to graphite is that lithium-ion battery manufacturers are not only depending on natural graphite, but also on synthetic graphite. Synthetic graphite is however not included in this assessment, but since the major country of source for synthetic graphite is concentrated to not only China but also Japan, the overall graphite ranking is lower than indicated in Table 4.3 for lithium-ion battery manufacturers.

Manganese, nickel, aluminum and copper are four materials that are classified with a medium-high ranking for social sustainability risk, which is indicated with the orange color for total impact. These materials still depend on countries whose social risk performance can be questioned, but since there is a more extensive geographical spread of these countries compared to cobalt and graphite, the total social impact is less. Lithium is the only material within the cluster of minerals and metals that do not depend on a country that has a high social risk in any of the assessment. However, it should be highlighted that several of the exiting refineries and suppliers of lithium hydroxide are located in China, which is not included in this assessment. Hence, taking this into consideration the overall social ranking for lithium should be somewhat higher.

Finally, it can be concluded that the materials included in the cluster of chemicals do not possess any social risk for lithium-ion battery manufacturers according to this assessment. However, since the primary raw material source of the chemicals are not taken into consideration, this assessment is based on the supply market for the specific battery products which might influence the outcome. Japan, the United States and Germany are included as the main countries for supply and none of these are ranked specifically low in any of the social impact ranking. The United States is indicated to be somewhat weak in working conditions and political stability according to The World Bank [2016] and International Trade Union Confederation [2014] respectively, which is illustrated with yellow and orange colors in Table 4.3. However, these factors do not affect the overall social risk impact that is weighted for all the including chemicals.
4.4. Summary of Contextual Study

This chapter highlights the characteristics of the including material in a lithium-ion battery cell. The identified critical materials are summarized according to the different clusters of materials. The included minerals, metals and chemicals are represented in Table 4.4, 4.5 and 4.6 respectively.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Unique Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>Included in the cathode active material. The main country of raw material supply is the D.R. of Congo, a country which also has negative sustainability impact. The metal is both rare and price-volatile but has good possibilities for recycling. Additionally, cobalt is ranked as a critical mineral by the European Commission.</td>
</tr>
<tr>
<td>Graphite</td>
<td>Included in the anode active material, both as natural and synthetic graphite. China is the main country of raw material supply, with over 65 percent of global mine production. Graphite is ranked as critical material by European Commission, and there are very limited recycling possibilities.</td>
</tr>
<tr>
<td>Lithium</td>
<td>Included in the cathode active material. The majority of conversion plants exist in China, and the related geopolitical risk has lead to significant price increases. Lithium is not defined as a critical material, however close to the threshold. The recycling possibilities are limited but are increasing.</td>
</tr>
<tr>
<td>Manganese</td>
<td>Included in the cathode active material mainly because of its low price, good availability, and favorable electrochemical behavior. Mine production is distributed across countries, with South Africa as the largest producer. The recycling possibilities are negligible.</td>
</tr>
<tr>
<td>Nickel</td>
<td>Included in the cathode active material and makes up the largest volume share. Big reserves exist that are spread globally. Nickel price is relatively inexpensive but volatile. During 2016 the recovered nickel represented 43 percent of the consumption.</td>
</tr>
</tbody>
</table>
### Table 4.5.: Summary of critical metals characteristics.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Unique Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Included in the cathode as the current collector. China is the main country of supply, representing more than 50 percent of the global mine production. Good possibilities for recycling.</td>
</tr>
<tr>
<td>Copper</td>
<td>Included in the anode as the current collector. The global mine production is geographically spread out, with Chile as the largest producer, followed by Peru. Good possibilities for recycling.</td>
</tr>
</tbody>
</table>

### Table 4.6.: Summary of critical chemicals characteristics.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Unique Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>One of the battery cell’s main components as it enables the ion flow in the cell. The electrolyte is dependent on high purity solvents that are volatile and flammable. The primarily used materials are LiPF6 salt and EC, EMC and DMC organic compounds. Posses no social sustainability risk.</td>
</tr>
<tr>
<td>Separator</td>
<td>One of the battery cell’s main components, where the separator is a porous membrane that prevents the cathode and anode to touch. It consists of plastic compounds such as PP and PEP. The environmental and social impacts are limited.</td>
</tr>
<tr>
<td>Other Chemicals</td>
<td>Included as binders and solvents in both the anode as CMC and SBR, and in the cathode as PVDF and NMP. They assure adhesion to the metal foils as well as assist the electron conduction. The solvents are flammable and NMP is toxic to environmental health. Posses no social sustainability risk.</td>
</tr>
</tbody>
</table>
5. Findings and Analysis

This chapter contains the empirical findings from the conducted expert interviews. It includes an assessment of material criticality for the critical materials in a lithium-ion battery cell, together with the main drivers for profit impact and supply risk for the purchasing environment. The chapter also includes a sustainability evaluation of the environmental and social risks related to the material, and potential risk mitigation strategies.

5.1. Assessment of Material Criticality

The empirical findings support the fact that several of the direct materials in lithium-ion batteries possess unique characteristics, which affects the purchasing environment in different ways. In accordance with the developed theoretical reference in Chapter 2.3, the critical direct materials are evaluated based on profit impact and supply risk. The results are derived from inputs from interviewed experts and supported by conclusions drawn from the technical literature review in Chapter 4.1 and 4.2.

Figure 5.1 illustrates the result of the classification assessment for the critical direct materials. The material’s location in the matrix indicates the strategic importance in purchasing [Kraljic 1983] and is further presented in the following sections.

![Material Classification Matrix](image)

**Figure 5.1.:** Material classification matrix of the including critical direct material in lithium-ion batteries.

The input gathered from the expert interviews indicates that the majority of the included several materials represent an extensive strategic importance for lithium-ion battery manufacturers. The materials experience both high profit impact, as well as high supply risk, leading to that the domi-
nant material category is strategic items. Based on the amount of materials located in the different classification areas, the purchasing portfolio looks as follows:

- **Leverage items** 5% Consist partly of other chemicals.
- **Strategic items** 65% Consist of cobalt, lithium, nickel, graphite, separator, electrolyte and partly copper.
- **Non-critical items** 15% Consist of manganese and partly other chemicals.
- **Bottleneck items** 15% Consist of aluminum and partly copper.

## 5.2. Profit Impact

The main drivers for the profit impact are the material’s *purchasing cost* and the *business importance* according to the theoretical reference developed in Chapter 2.3. The profit impact evaluation is based on a conducted bill of material for a lithium-ion battery cell, as well as a technical investigation of the materials contribution in the battery cell. Table 5.1 presents an overview of the profit impact evaluation and the classification assessment is described below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total Ranking</th>
<th>Purchasing Volume</th>
<th>Purchasing Cost</th>
<th>Business Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>10</td>
<td>18.6%</td>
<td>15.2%</td>
<td>High</td>
</tr>
<tr>
<td>Separator</td>
<td>10</td>
<td>3.3%</td>
<td>16.1%</td>
<td>High</td>
</tr>
<tr>
<td>Graphite</td>
<td>8</td>
<td>25.2%</td>
<td>20.9%</td>
<td>Medium</td>
</tr>
<tr>
<td>Cobalt</td>
<td>8</td>
<td>2.3%</td>
<td>10.9%</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Lithium</td>
<td>7</td>
<td>2.8%</td>
<td>3.3%</td>
<td>High</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>7</td>
<td>11.6%</td>
<td>8.7%</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Copper</td>
<td>5</td>
<td>8.8%</td>
<td>6.9%</td>
<td>Medium-Low</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>5</td>
<td>14.3%</td>
<td>10.4%</td>
<td>Low</td>
</tr>
<tr>
<td>Aluminum</td>
<td>3</td>
<td>4.3%</td>
<td>1.6%</td>
<td>Medium-Low</td>
</tr>
<tr>
<td>Manganese</td>
<td>2</td>
<td>2.2%</td>
<td>0.3%</td>
<td>Low</td>
</tr>
<tr>
<td>Other (not included)</td>
<td>-</td>
<td>6.6%</td>
<td>5.7%</td>
<td>-</td>
</tr>
</tbody>
</table>

The total profit impact ranking in the second column in Table 5.1 is an equally weighted value of the percentage of total purchasing cost and business importance. The purchasing volume is not included in the weighted ranking since it is indirectly included as part of the purchasing cost. However, the percentage of total volume indicate whether the total purchase cost is mainly driven by the ordered volume or the material price and is therefore presented in the table. The last row is added in the
5.2.1. Purchasing Volume

The purchasing volume of each material is based on the weight percentage of the material that is included in the battery cell. The exact breakdown is not widely presented or easily found in literature because of its strategic importance for cell performance and the battery manufacturers competitiveness. Therefore, the results are conducted together with experienced technical experts and summarized into a detailed bill of material. The information that has been given by experts have additionally been cross compared with each other to assure the correct order of magnitude. Due to sensitive information, the exact numbers are left out in this report, but the percentage presented in Table 5.1 gives an indication of how the material weight is allocated in the battery cell.

The developed bill of material is built upon the critical materials in a lithium-ion battery, but what is important to note is that some of the numbers presented in Table 5.1 take whole components into account. For instance, the electrolyte and separator, thus representing a large volume percentage for these materials. While the materials included in the cathode are broken down separately.

5.2.2. Purchasing Cost

The purchasing cost is based on the material purchasing volume, presented in Table 5.1, and the material price. The exact purchase price for battery specific material is considered as confidential and is intentionally left out in this report due to ethical aspects. However, the column of purchase cost in Table 5.1 gives an indication of whether the price is relatively high or low for the materials. The including material prices are primarily based on the listed prices for the time of this study i.e. May 2017, but is modified with information gathered from the interviews. The modification of prices is done since the materials included in lithium-ion batteries do not directly correspond to the listed price. Expert M highlights this issue because of the need for high purity grade materials, which is very unique for the battery manufacturing industry. Other material prices that are not listed on the stock exchange is instead based only on inputs from industry experts.

Compilation of the information from the conducted interviews show that the four materials representing the highest purchasing costs are graphite, separator, nickel and cobalt. They altogether represent 60 percent of total cell cost and are the four materials affecting the profit impact the most. The empirical findings indicate that the lithium-ion battery manufacturers are exposed to many materials with highly volatile pricing. The high volatility in prices impacts the overall business profit and causes variations in the purchasing environment. Expert B, Expert I, Expert K and Expert N stress this issue as a challenge related to the minerals, especially for cobalt and lithium. Figure 5.2 illustrates
the listed cobalt raw material price during the last five years [LME 2017]. It can be deducted that during the period of October 2016 to April 2017, the price increased by over 90 percent. Expert K highlights the challenge of price fluctuations accordingly:

Battery manufacturers are exposed to a very big challenge when it comes to material cost, cobalt and lithium are the worst. The price fluctuations can really hit your business hard, which is something you need to be aware of - Expert K

Furthermore, Expert K specifically highlights lithium as a material that has been exposed to a high increase in price the last years because of the supply shortage in China, and Expert B expresses concerns related to volatile pricing:

It is important to consider pricing over time because it varies heavily for both the raw material itself and the needed material format for battery components. Currency changes and volatility in raw material prices add a unique complexity and demand a new field of study for lithium-ion battery manufacturers - Expert B

The conducted expert interviews showed that with respect to the cluster of chemicals, the separator is the material with the lowest purchasing volume at 3.3 percent but the largest purchasing cost 16.1 percent, as presented in Table 5.1. This indicates a high purchase price for the material demanded for a battery application. The chemicals are not dependent on primary sources that experience heavy fluctuations in price, but instead have relatively stable prices that do not affect the purchasing en-
vironment noteworthy. Aluminum and copper, used as metal foils in the battery both make out a small percentage of total material cost [Expert D], 1.6 and 6.9 percent respectively, which result in less contribution to profit impact.

5.2.3. Business Importance

The business importance ranking is dependent on the specific material’s function for the battery cell performance and its influence on business growth. Both Expert M and Expert J highlight that all the including materials have a high importance and impact for the battery cell performance. However, the interviews show that there still exist some differences between the critical materials. The difference is based on how much the material contributes to the overall business importance and future growth, as well as to what extent the material’s quality can be stretched without influencing the battery functioning. This study of the business importance compares the material’s importance relative to each other with the purpose to give a ranking of their overall profit impact. The assessment is done according to a scale from low to high based mainly on the empirical findings and to some extent to the technical literature review. The classification of business importance is done according to the following criteria and presented for each material in Table 5.2.

- **High** - The material highly contributes to the overall cell performance and the material quality cannot be stretched to any extent without influencing the battery functioning.
- **Medium** - The material contributes to the overall cell performance but can with difficulties be included in more material formats if taken careful consideration.
- **Low** - The material contributes to the overall cell performance but the required material characteristics are not unique to the industry.

<table>
<thead>
<tr>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium</th>
<th>Medium-High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Chemicals</td>
<td>Aluminum</td>
<td>Graphite</td>
<td>Cobalt</td>
<td>Lithium</td>
</tr>
<tr>
<td>Manganese</td>
<td>Copper</td>
<td></td>
<td>Electrolyte</td>
<td>Nickel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Separator</td>
</tr>
</tbody>
</table>

In the interviews, Expert N and Expert D point out that lithium, cobalt and nickel are the most important minerals for lithium-ion battery manufacturers. These are the main components in the cathode active material and highly influence the battery performance in terms of energy density. In line with that, Expert K also sees lithium and nickel as highly important for the business, but concludes that cobalt may have less importance in the future. This is supported by the fact that many research and development projects are being performed in order to reduce the amount of cobalt in batteries [Expert K]. The fact that cobalt is of high importance for lithium-ion battery manufacturers today
but is likely to decrease in the future, result in a medium-high ranking for the business importance.

Both Expert N and Expert K identify the separator as highly important for the battery’s performance. The need of a high-quality separator is essential in order to achieve the desired cell characteristics and ensure safety in the battery cell. Additionally, the component is very unique for the battery manufacturing industry, adding further importance to secure long-term supply from limited amount of suitable suppliers, hence increasing the business importance. Expert M points out the strategic importance of the electrolyte, which influences the cyclic performance of charge and discharge. The reason for why it is classified as medium-high risk is because there exist other compositions of the electrolyte solution from various suppliers, thus resulting in a somewhat less dependence on the electrolyte chemicals in terms of impact on the business growth.

Expert D brings up the business importance of graphite with good quality for the lithium-ion battery manufacturers, but this is not specifically highlighted by other experts to the same extent. Instead, Expert O focuses on the optimization of the mixture between natural and synthetic graphite as one of the main important factors for the business. The ranking of business importance for graphite in this assessment is therefore set to medium.

Aluminum and copper constitute the current collectors of the cathode and anode respectively, they both need to pass the desired material purity in order to contribute to the battery cell performance [Expert D and Expert E]. The foils are necessary in a battery cell and cannot be substituted with other materials. However, these metals exist in various thickness and depending on the thickness contributes to either energy density or power density for the batteries [Expert N]. The flexibility regarding the different material formats, as well as the fact that the material is not only unique for the battery manufacturing industry, is the reason to why they are assessed with a medium-low business importance.

Expert D, Expert K and Expert M indicate that manganese is of low business importance for the lithium-ion battery manufacturers. This is supported by the fact that the material is relatively cheap, easily accessible and is only included in small amounts in lithium-ion batteries. Other chemicals that are used during the manufacturing process are not considered as materials with high business importance by any of the interviewed experts. These chemicals are needed in the cathode and anode but are not a part of the active material or the collectors, hence they are ranked with a low business importance.

5.3. Supply Risk

The main drivers for supply risk are; material availability, product supply, geopolitical risk, and the possible purchasing flexibility related to the material. Table 5.3 presents the supply risk evaluation
of the critical direct materials in a battery cell. The evaluation is based on an analysis of both the primary source availability, as well as the prepared material in a format according to the needed battery purity. The total ranking of supply risk in the second column is an equally weighted value of material availability, geopolitical supply risk, product supply and purchasing flexibility. Furthermore, purchase flexibility includes two different perspectives of various make-or-buy opportunities and the related storage risk for the materials. These are presented separately due to their different assessments but weighted equally in the compilation of the purchasing flexibility.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total Ranking</th>
<th>Material Availability</th>
<th>Product Supply</th>
<th>Political Risk</th>
<th>Purchasing Make-or-Buy Options</th>
<th>Flexibility Storage Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>9.5</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Lithium</td>
<td>8.5</td>
<td>Med-High</td>
<td>Med-High</td>
<td>Med-High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Nickel</td>
<td>7.3</td>
<td>Medium</td>
<td>High</td>
<td>Med-High</td>
<td>Med-Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Copper</td>
<td>6.8</td>
<td>Medium</td>
<td>Medium</td>
<td>Med-High</td>
<td>Med-High</td>
<td>Medium</td>
</tr>
<tr>
<td>Separator</td>
<td>6.7</td>
<td>N/A</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Graphite</td>
<td>6.5</td>
<td>Med-Low</td>
<td>Med-Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6.5</td>
<td>Medium</td>
<td>Medium</td>
<td>Med-High</td>
<td>Med-High</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>5.3</td>
<td>N/A</td>
<td>Med-High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Manganese</td>
<td>4.0</td>
<td>Low</td>
<td>Low</td>
<td>Med-High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>3.3</td>
<td>N/A</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

5.3.1. Material Availability

The assessment of material availability is dependent on the availability of the primary sources. Since the chemicals do not originate from raw material reserves in the same way as the natural resources, the supply risk in terms of material availability is set to not applicable according to recommendations from Expert K. The assessment of material availability is hence mainly focused on the minerals and metals since they depend on natural resources. If there is a limited availability of natural resources and recycling possibilities, the supply risk is considerably higher than if there exist a large amount of material at an affordable price. Some materials may additionally be limited to a few number of areas, or located in rural areas, making them hard or expensive to access and hence increasing the related supply risk. The classification of material availability is done according to the following criteria and presented for each material in Table 5.4.

- High - Natural resources with high risk of depletion, high material criticality and low recycling opportunities.
• Medium - Natural resources with low risk of depletion or high possibilities for material recycling.

• Low - Not a limited primary source and available in multiple geographical locations.

<table>
<thead>
<tr>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium</th>
<th>Medium-High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>Graphite</td>
<td>Nickel</td>
<td>Lithium</td>
<td>Cobalt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminum</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The minerals are natural resources that heavily depend on the ores’ specific location and their geographical areas. Cobalt is the material that is ranked with high risk for primary source unavailability in this assessment, as presented in Table 5.4. Cobalt has a high geographical concentration with the majority of its mine production in the D.R. of Congo. The material is mainly mined together with other primary minerals and does not exist in a large extent. Even though there exist recycling possibilities for cobalt, as previous reviewed in Chapter 4.2, the limited availability of cobalt as a primary source is of concern for lithium-ion battery manufacturers.

Plenty of lithium resources exist but these are hard to access at an affordable price [Expert N]. Nurmi [2017] emphasizes this issue by highlighting the challenges for the mining industry and further points out that there exist plenty of natural resources but with related exploration challenges. Some of the minerals are located in inaccessible reserves, deeper in the ground, with lower concentrations and several challenges to the exploration process [Nurmi 2017]. Conclusively, this results in a relatively high supply risk due to limited material availability, not only from a geological point of view but also from an economical. Lithium is ranked with a medium to high risk of primary source unavailability mainly because of its so far insignificant recycling possibilities, as well as resource demanding exploration.

The material availability of nickel has been highlighted during the interviews with Expert A and Expert N. However, the urgency of unavailability is of less extent than for lithium and cobalt according to them, therefore it is ranked with medium risk. Expert N considers the output of nickel as quite limited but would not classify it as a high supply risk. Additionally, there exist good possibilities for material recycling [USGS 2017].

The supply risk related to material availability for both copper and aluminum is ranked as medium. It has not been specifically highlighted by the experts but the materials still depend on natural resources. The fact that there exist good recycling possibilities for both copper and aluminum [USGS 2017] hence limit the risk related to material unavailability.
The possibility to blend natural graphite together with synthetic graphite in the anode brings down the supply risk with respect to material unavailability for lithium-ion battery manufacturers. Expert K points out that a lot of the natural graphite used in battery manufacturing is sourced from China but that the synthetic graphite is primarily coming from Japan. Additionally, there is a low risk for resource depletion and on-going studies for improved recycling possibilities [European Commission 2015b]. The risk for primary source unavailability for graphite is therefore considered as medium-low in this assessment.

The material availability of manganese supply is not specifically highlighted as a concern since it is confirmed that there exist a lot of manganese in China to an affordable price [Expert N]. Even though the USGS [2017] finds the recovery possibilities for manganese as negligible, this is not an issue brought up by any expert with concerns to the material unavailability. Expert J further points out that the manganese used in the battery manufacturing process is of very low volume which can be recovered, hence resulting in a low risk for material unavailability.

5.3.2. Product Supply

As a result of the rapid industry development, lithium-ion battery manufacturers are exposed to an unbalanced business environment with limited product supply. This issue puts high demand on the purchasing activity in order to identify suitable suppliers offering the demanded battery product. The product supply depends on factors related to the number of available suppliers, the competitive demand, and how specific the requested material is to the battery industry. Additionally, the product supply risk also considers the difficulties with intellectual properties that are required for the production, which is limiting the potential for an increased product supply base in the future. The classification of product supply availability is done according to the following criteria and presented for each material in Table 5.5.

- **High** - The number of suppliers offering the required battery grade material is limited and difficulties exist to increase a qualified supply base and process flow.
- **Medium** - The number of suppliers offering the required battery grade material is limited but opportunities exist to increase the supply base.
- **Low** - Multiple suppliers offer the required battery grade material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium</th>
<th>Medium-High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>Graphite</td>
<td>Copper</td>
<td>Lithium</td>
<td>Cobalt</td>
<td>Nickel</td>
</tr>
<tr>
<td>Other Chemicals</td>
<td>Other</td>
<td>Aluminum</td>
<td>Electrolyte</td>
<td>Nickel</td>
<td>Separator</td>
</tr>
</tbody>
</table>
In order to obtain the desired cell performance, high-quality materials named battery grade, and cleanliness in all steps of the value chain is necessary [Expert N]. The different rankings presented in Table 5.5 indicate how the necessity differ between the materials. The requirement of high purity materials makes the assessment regarding product supply to one of the most critical potential supply disruption for lithium-ion battery manufacturers.

According to Expert N and Expert O, one major concern for lithium-ion battery manufacturers is the difficulty to qualify process flows in between different upstream activities. This is particularly an issue for the including minerals since they do not only depend on the availability of the primary source, but also on the related refineries’ capacity and that they can live up to the quality requirements. There exists more available mines than refineries [Expert N], which leads to a challenge to secure material supply even if the raw material exists. The risk of supply disruptions in multiple steps of the inbound supply chain is additionally highlighted by Expert O:

*The unbalance between available mines and refineries is a challenge, with a larger risk for unavailable capacity in the refineries than in the mines. Also, it is not easy to change these collaborating actors since they depend on each other. Meaning that even if there exist mines that battery manufacturers can work together with, but there is a lack of suitable refineries, there is still in an unfavorable position that needs to be addressed - Expert O*

The risk for unavailability of battery product supply is ranked as high for cobalt, nickel and the separator. The geographical spread of cobalt refineries is wider than for the mine production. These refineries do on the other hand highly depend on the cobalt supply that originates from the D.R. of Congo, which causes an increased supply risk also for the refineries. Furthermore, Expert O, points out the supply of cobalt as the most critical question to solve in terms of material supply for lithium-ion battery manufacturers and additionally highlights the challenges to secure a local supply chain.

The separator is very specific for the battery industry and there are not many suppliers that can produce a high-quality product. Expert N defines the existing supply market of the separator as an oligopoly. Because of the limited number of available suppliers, the separator is ranked with a high risk for unavailability of product supply.

Expert K, Expert M and Expert N indicate that both lithium and electrolyte also are exposed to a relatively high product supply risk because of limitations in the existing supply market structure. Expert N points out that the availability for lithium is not going to restrain battery manufacturers but that refining of lithium is going to be a constraint for the next 5 years or so. The product supply risk ranking of the two materials are therefore medium-high.
The organic carbonates included in the electrolyte are used in other industries, so the supply market is somewhat developed, with the main electrolyte suppliers located in China and Japan [Expert K]. However, the salt included in the electrolyte is based on lithium, increasing the supply complexity in some way due to the limitation of the mineral supply.

Expert D and Expert E point out that the aluminum and copper require very high purity grade and that the manufacturing process needs to be perfect. If dirt gets into the batteries it will cause devastating consequences for the battery performance. Furthermore, Expert C concludes that battery foils, in general, should be as thin as possible, but when the thickness gets really thin it enforces further challenges for the supplier’s processes and could trigger problems in the production. The challenge of finding suitable suppliers that can meet these metal foils requirements results in a medium rating for the product supply risk.

The resulting materials; manganese and other chemicals, need of high purity and quality is of somewhat less importance for lithium-ion battery manufacturers. The associated risk in terms of product supply has not been raised by any of the experts, hence resulting in a low ranking for product supply risk.

5.3.3. Political Supply Risk

Lithium-ion battery manufacturers depend on unique materials and natural resources that can be supplied from only a few numbers of geographical areas. This results in a high dependency on the concerned countries, limits the flexibility in supplier selection, and affects the possibilities for inventory. The risk of increased purchase cost, delivery time, and negative social influence are higher in the cases when the material is sourced from an area exposed to geopolitical risks. The geopolitical supply risk covers the entire supply chain and the upstream activities can all affect the supply risk of material to the manufacturing facility. The risk is assessed according to the material’s related political instabilities that are reviewed in Chapter 4.3.2. Input for the geopolitical risk associated with the suppliers of battery grade materials has been derived from the experts interviews. The classification of political supply risk is done according to the following criteria and presented for each material in Table 5.6.

- High - There is a high concentration of primary sources and/or suppliers of battery grade materials in countries with high political instability according to WGI rankings.

- Medium - There is a geographical spread of the primary sources and suppliers of battery grade materials. However several of them still suffer from political instability according to WGI rankings.

- Low - The majority of primary sources and suppliers of battery grade materials are located in countries with low geopolitical risk.
Table 5.6.: Risks for supply disruptions due to political instability

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<th>Low</th>
<th>Medium-Low</th>
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<tr>
<td>Separator</td>
<td>Nickel</td>
<td>Cobalt</td>
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<td>Electrolyte</td>
<td>Copper</td>
<td>Graphite</td>
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<td>Other Chemicals</td>
<td>Manganese</td>
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<td>Aluminum</td>
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During the interviews, the challenge to secure the cobalt supply has been highlighted recurrently by several experts. It is considered as one of the major issues for obtaining a sustainable inbound supply chain by Expert O and Expert N, specifically related to the source’s political instability. The large share of cobalt that originates from the D.R. of Congo brings a high geopolitical supply risk, as presented in Chapter 4.3.2. This leads to that actors downstream are heavenly dependent on supply with risk for disruption and the concerns are expressed as:

*The most critical in my perspective is how to solve the cobalt question. Ultimately you want to avoid the dependency on the Democratic Republic of Congo, but that will be a challenge since that’s where the majority of the deposit sources exist - Expert O*

Lithium has a wider geographical spread of its mine production than cobalt but the interviews reviled that the majority of the conversion plants to produce lithium concentrates for battery applications are located in China [Expert K]. Lithium has furthermore been subject to high price increases in the last years because of supply shortages and repressed production in China [Expert N]. This political instability promotes a relatively high ranking for its geopolitical supply risk.

None of the remaining critical materials have further been addressed in any of the interviews with concerns to their geopolitical risk. Therefore, the associated ratings have only been assessed based on the location of the mine production and the country’s related political risk according to the WGI and the geographical spread of the sources. Natural graphite is heavily dependent on the political instability in China. It has additionally been ranked by the European Commission [2015b] as a critical material, partly with respect to the associated high political risk rating for both China and India, the world’s second largest producer of natural graphite. Manganese, nickel, aluminum and copper are all ranked with a medium-high social risk in Chapter 4.3.2, hence influencing the assessment of the political risk here as well. The remaining materials are the chemicals which are all assessed with a ranking of low political risk since the countries of source represent an overall low social impact.
5.3.4. Purchasing Flexibility

The measurement of purchasing flexibility is over-bridging two different factors, make-or-buy opportunities and the risk associated with storage of the particular material. This is an indicator whether the purchasing company can mitigate the risk of supply disruptions by either changing the ordered material format, or by keeping the critical material in stock. The two perspectives are weighted together as one in the total ranking evaluation illustrated in Table 5.3.

Make-or-Buy Options

In order for the battery to function as desired, the materials need to be of specific format, character and properties to suit the specific cell chemistry. The including materials might be able to be exchanged as a result of R&D investments over time, but today leaves little flexibility for the producing battery companies. However, some components can be purchased in different formats and then be processed and partly manufactured in-house to suit the specific properties needed in the cell. In other words, it can be viewed as a flexibility regarding the opportunities to vertically integrate. The classification of make-or-buy options affecting the supply risk is done according to the following criteria and presented for each material in Table 5.7.

- **High** - The material is very hard to process in-house because of high process complexity and need for specific industry expertise.
- **Medium** - The material can be processed in-house but requires high investments and many resources.
- **Low** - There are one or more levels of vertical integration that is possible with a short pay-back time.

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<th>Table 5.7.: Risks for low purchasing flexibility due to limited options of vertical integration</th>
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<td>Manganese</td>
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<td>Other Chemicals</td>
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During the interviews, the decision of whether to make or buy the material has been brought up by several experts as an important opportunity for lithium-ion battery manufacturers. The level of vertical integration affects both the level of control for the organization, as well as the purchasing price. The level of control is especially important in battery manufacturing when the performance of the battery is highly dependent on the material quality. The benefits of purchasing materials upstream is expressed related to the quality aspect as such:
The further downstream in a material’s process, the likeliness that the product will be different is higher. Therefore, the more upstream you include the material, the less sensible it is - Expert N

The process to produce lithium hydroxide in-house is very complex and therefore not considered as an option for lithium-ion battery manufacturers [Expert K]. The same is true for graphite manufacturing, which also has very low opportunities to make the material in-house. The market for the separator consists of only a few players [Expert N], indicating difficulties to vertically integrate. None of the interviewed experts have considered it as an option to produce the separator in-house, due to its high quality requirements. Limited options for vertical integration leads to low purchasing flexibility and therefore represents a high supply risk for lithium, graphite and the separator.

As highlighted earlier by Expert C, Expert D and Expert E, the foils used in the cathode and anode require a very clean and specific manufacturing process in order to make the foils as thin as they need to be. The high investments and knowledge required for the process are therefore resulting in a medium-high supply risk related to make-or-buy opportunities for these materials.

The electrolyte consists of several chemicals such as solvents, lithium salt and additives that are blended. There is an opportunity for lithium-ion battery manufacturers to choose whether to procure the electrolyte materials separately and then mix it in-house or as a mixture that is already compiled by the chemical manufacturer [Expert K]. However, the included additives are considered as very secret since they highly affect the overall cell performance and thus the competitive advantage for lithium-ion battery manufacturers [Expert N]. According to Expert K, the additives are very difficult to make, and it is further concluded that it is very hard for battery manufacturers to compete with chemical companies on this because of intellectual properties. Since there exist possibilities to mix the chemicals in-house the purchasing flexibility risk is rated to medium. This is similar to what is indicated for the other chemicals, hence resulting in a medium ranking for them as well.

The possible choices of varying material formats are primarily applicable for the active cathode materials, more specifically the nickel mineral. In the manufacturing process, nickel needs to be dissolved to sulfates in order to create the salt in the precursor - an important phase in the manufacturing process to obtain a good quality for the battery [Expert N]. For lithium-ion battery manufacturers, this results in a decision of whether to purchase the nickel in a solid state such as briquettes or powder form, or to purchase the material already in chemical format. The difference also means to either add sulfuric acid as part of the process in-house when nickel is purchased in solid state, or to purchase the material as already mixed nickel sulfate [Expert G]. The empirical study shows that there is a consensus among several experts, towards that it is economic preferable to purchase nickel metal and process nickel sulfate in-house.
Besides nickel, both cobalt and manganese also undergo the same process and are transformed from minerals to chemicals in the form of sulfates. Even though the process for all three materials is the same, it is not a favorable action for cobalt and manganese because of the lower volumes [Expert K], resulting in a medium rating for make-or-buy opportunities.

**Storage Risk**

Stockpiling can decrease the dependency on external actors and guard against potential disruptions or speculations. Limiting storage factors for lithium-ion battery manufacturers might be if the material’s characteristics is heavily affected by being kept in inventory, is very resource demanding when it comes to warehousing, or experience high capital accumulation. The cost and complexity of storage contribute to the supply risk and the more capital intensive the warehousing is, the higher is the risk of storage. The classification of storage risk is done according to the following criteria and presented for each material in Table 5.8.

- **High** - Storage highly affects the material characteristics and demand special treatment to mitigate negative impact. Additionally, storing of the material is associated with high capital accumulation.
- **Medium** - The material can be stored without influencing the technical performance, but should be avoided due to high capital accumulation and vulnerability in the material handling process.
- **Low** - The material can be stored without any major technical storage implications. It also has low capital accumulation due to relatively low material price.

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<td>Manganese</td>
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The distance to the supplier is a driving factor that impacts the considerations regarding what level of inventory that is considered as the best amount for the specific material. Being dependent on material that are tied to a limited amount of geographical areas limits the purchasing flexibility and increases the risk of failure during delivery. This results in a need of larger purchase volumes in order to have a backup on site, which is highlighted by experts:
The amount of materials kept in storage is heavily dependent on the distance to the source and the supplier’s location. With material transported from America and Asia, more exact inventory management is increasing in importance - Expert H

The two materials ranked with high storage risk are cobalt and lithium, as presented in Table 5.8. Expert F highlights the need for mitigating humidity exposure for cobalt sulfate since it can form lumps that obstruct the manufacturing process. Together with the fact that cobalt is transported long distance due to concentration in a few geographical locations, results in a need for inventory management but also high storage risk. Expert K points out that the heavily price fluctuations results in a need to limit the amount of materials held in stock. The financial driver regarding supply risk can be applied both for cobalt and lithium and is a highlighted issue accordingly:

The lithium and cobalt prices are fluctuating heavily, therefore, as a lithium-ion battery manufacturer, you would like to minimize the amount of stored products with these materials - Expert K

Lithium hydroxide is also very sensitive to humidity, which adds complexity to the warehousing. The challenges of storage and the associated risks are also expressed by Expert K as:

From a technical perspective, the only material that posses a high storage risk is the lithium hydroxide. Even just a minor humidity contribution might have an impact on the entire battery performance. The other materials need some considerations regarding sensitivity and safety, but compared to lithium these concerns are of limited importance - Expert K

The separator represents a large share (18 percent) of the cell’s material cost. It has a long shelf life and no special storage requirements, meaning that it results in a medium rating of the storage risk. Medium rating is also given to the electrolyte and other chemicals. There exist some storage risk for the chemicals included in the electrolyte due to that the chemicals are very flammable [Expert N]. Additionally, should the including lithium salt not be exposed to humidity [Expert M]. These characteristics need to be taken into consideration in material handling and storage and therefore add storage cost, which affects the supply risk indicator. Other chemicals include NMP, which may cause damage to human health. Expert N highlights this as a consideration in storage handling, and points out that specific requirements are needed in order to guarantee safety.

Additional materials that are ranked with medium storage risk are nickel, graphite and copper. That assessment is based primarily on the capital accumulation for these materials, and no specific storage considerations are highlighted by the experts. For the metals, neither copper nor aluminum are sensitive to temperature or humidity exposure, but the foils are on the other hand sensitive to external bumps that may damage the material. They require wooden boxes for transportation and storage to
avoid damage [Expert K], but do not add additional storage costs. Aluminum and manganese are ranked with medium-low and low storage risk respectively, since their material price is relatively low and therefore contribute with lower capital accumulation for lithium-ion battery manufacturers.

5.4. Sustainability Considerations

The lithium-ion battery manufacturing industry is challenged with respect to environmental issues that the materials contribute with, as well as the social impact related to the country of source. Based on that sustainability assessment in Chapter 4.3, a weighted sustainability value for each material is conducted. The compiled sustainability value together with the size of the purchased volume is applied to the material classification matrix to indicate the associated sustainability risk, and illustrated in Figure 5.3. The environmental risk associated with each material is represented in the left half, while the social risk is represented on the right. The combination of these two assessments can be considered as an indicator for whereas the company should prioritize the resources in terms of environmental and social sustainability, and to what extent.

As presented in Figure 5.3, cobalt contributes with the highest sustainability risk both with respect to environmental and social impact. Graphite is presented as a material with high sustainability concern but that might be somewhat misleading for lithium-ion battery manufacturers since there exist a possibility to mix the natural graphite with synthetic graphite, which has a lower social risk. Nickel, manganese and copper are other materials with relatively high sustainability impacts. The environmental and social issues that are associated with a majority of the strategic materials has also been expressed as critical factors by experts. There is an experienced external pressure regarding the need
to assess sustainability challenges for the actors operating in the industry, and Expert H expresses the concerns as:

*I feel that there’s an external pressure regarding sustainability considerations in our battery operation. The request is coming from both customers and governmental authorities, these people might consider this as a dirty business* - Expert H

Moreover, the empirical findings highlight a need for that sustainability impact should be a prioritized evaluation criteria already when selecting materials and suppliers. These are further elaborated on below according to:

- **Material selection process** - Considerations related to the chosen material to be included in the battery cell with respect to its environmental impact, the format of the specific material, the requested packaging format and the delivery mode.

- **Supplier selection process** - Considerations related to the chosen supplier’s activity, the distance from the source as well as agreements in the supplier contract.

### 5.4.1. Material Selection

The choice between material format is highlighted to have different environmental impacts since it can affect the amount of material that is transported, as well as the safety in material handling and manufacturing [Expert I and Expert G]. From an environmental perspective, there exists an aim to minimize the amount of deliveries to reduce the greenhouse gas emissions. From a social perspective, the working conditions and safety assurance is of high importance.

Generally, the included materials in a lithium-ion battery cell are very specific and hard to substitute, but in the cases where it is possible, sustainability considerations should be included in the material selection process. This can be done by either ordering the material in another format or by compensating for the potential environmental impact the material is causing. Vertical integration is one way for lithium-ion battery manufacturers to order the material in another format. The possibility for vertical integration vary between the materials, as presented in Chapter 5.3.4. The sustainability impact is furthermore influenced to various extents. The sustainability concerns related to nickel material vertical integration is expressed as:

*There are different possibilities for getting the needed nickel sulfate, either from nickel in metal form or bought as nickel sulfate in salt or liquid formats. Every time that we have looked at it, there is a strong economic benefit with buying nickel in metal form and making the nickel sulphate ourselves. It also affects the transportation costs since the nickel metal is more concentrated, which make the whole delivery volume decrease by a factor 10. So looking at the overall picture, buying nickel in metal form*
is an obvious environmental and economic benefit - Expert G

Expert G also highlights the social risks related to the vertical integration possibilities of nickel since different material formats also affects the safety related to the material handling and the manufacturing process differently:

We have the principle of prioritizing safety first. Therefore, the material format is also of high importance in manufacturing for the cause of the workers. Purchasing nickel in metal form is a lot safer than the chemical (that we will need in the end), which is also an additional reason to why we have chosen to vertical integrate in this way - Expert G

The material selection in terms of sustainability has shown to be of high importance for graphite. Since graphite is the only material in lithium-ion batteries that to some extent experience purchasing flexibility in terms of the mix between natural and synthetic graphite the sustainability impact can be influenced through purchasing decisions. Expert O points out the optimization of the graphite mixture in the anode as one of the main challenges to achieve a sustainable inbound supply chain but continues with expressing concerns for the environmental impact associated with the production of synthetic graphite. Hence, the blend of graphite does not only has an economic and performance trade-off but also a third sustainability aspect that needs to be taken into consideration in material selection.

The empirical findings indicate that the purchasing department should have close contact with manufacturing so that the material requirements in production can be met. For instance, metals foils are transported in coils with various widths depending on the supplier’s capacity and the buyer’s requirement [Expert L]. Expert E highlights that it is important to consider the different widths, already in the purchasing activity, in this way, material scrap can be minimized and thus also limit the negative environmental impact. The close contact between the purchasing and manufacturing departments can limit the environmental impact by making the right selections already when ordering the materials.

Very wide coils may cause shipping problems, whereas the production can benefit from using wide coils to achieve higher efficiency. An important factor to consider is how the choice of ordered material can be optimized to the requested formats in production, thus decreasing the scrap and excess material - Expert E

The findings indicate that a close discussion between the manufacturing and purchasing department should be held regarding the packaging of the materials. The packaging has an impact on the environment but also on the material quality [Expert M] and there is a trade-off between damaging the material and the additional packaging in an environmental perspective. Besides discussions with suppliers regarding packaging, the discussion should also include whether or not the packaging is
returnable. For the metals in the battery manufacturing industry, it is common that returnable packaging is used for near geographic locations and that disposable packaging is used for shipments to other continents [Expert L]. The choice between returnable or disposable packaging is made based on both environmental and economic grounds, in other words, this packaging selection made in purchasing may also include the sustainability department.

5.4.2. Supplier Selection

The lithium-ion battery manufacturing industry is also challenged with respect to the social sustainability impact that the operation contributes with. For the natural resources that are purchased from countries performing weakly in the sustainability assessment in Chapter 4.3.2, it becomes more important to assure that the suppliers are running their operation in an acceptable way. Expert G, stresses the need to consider these aspects early in the supplier selection process accordingly:

> Generally speaking, it is better to investigate the supplier’s sustainability performance early on in the selection process. As the time passes by, the degree of freedom and opportunity to have an impact decreases - Expert G

Expert G also stresses that there is nothing that can compensate for a supplier that does not meet the sustainability demands. That creates incentives to changing suppliers, which is a long and complex process for lithium-ion battery manufacturers with respect to the unique material characteristics. These challenges are further emphasized by other experts accordingly:

> Sustainability is a very crucial concern for lithium-ion battery manufacturers. When it comes to critical minerals, such as lithium and cobalt, there is a need for careful material procurement processes. This also includes logistics aspects with activities that all need to be performed from a CSR perspective, in order to avoid a negative company image - Expert B

> Having suppliers that operate in an ethical manner, is of high importance and should be a criterion in the supplier selection process - Expert F

As indicated above, many experts experience the sustainability concerns as of big importance for the lithium-ion battery manufacturers. However, there exist some ambiguity related to what extent that is legitimate. Expert N explains that the experienced criticism may be somewhat over-dramatically phrased, and that other industries are not being challenged as much, even though they contribute with negative sustainability impact by using similar or same materials. Additionally, the empirical findings indicate that experts operating within the industry experience a lack of suitable measurements and indicators for the sustainability impact [Expert H], but to have suppliers in nearby locations have shown to simplify the process of sustainability assessment [Expert G].
Finally, the importance to consider supplier selection early on in the purchasing process is strength-
ened also by the fact that the upstream industries are slower than the lithium-ion battery industry,
increasing the importance of making right decisions directly. This is expressed by Expert N as:

*Generally speaking, minerals are probably going to be one of the biggest challenges for the inbound
supply chain, especially for cobalt and nickel. The mining industry is extremely conservative and slow,
making it hard to impact* - Expert N

### 5.5. Supply Risk Mitigation Strategies

The material evaluation assessment performed in Chapter 5.1 shows that 65 percent of the purchasing
portfolio for lithium-ion battery manufacturers are represented with materials ranked as strategic
items. Similar to what is addressed in the literature by Kraljic [1983] and Lapko et al. [2016], these
strategic items with high material criticality demand suitable risk mitigation strategies. During the
interviews, strategies of how to mitigate the material supply risk have been addressed. This chapter
presents the critical factors of consideration for lithium-ion battery manufacturers, in order to limit
the risk of supply disruption and to obtain a sustainable inbound supply chain.

#### 5.5.1. Diversification of Suppliers

Diversification of suppliers can favorably be done by having multiple suppliers that are preferably
spread over a large geographical area in order to hedge the supply risk. This strategy has been iden-
tified as the most important prevention to reduce disruptions in supply [Beer 2015], and in similarity
is also highlighted as a potential supply risk mitigation strategy applicable for lithium-ion battery
manufacturers. Expert B expresses the consideration of supplier diversification as a good strategy
accordingly:

*For the critical products in your business, it’s important to know how to handle a potential failure from
one supplier. Therefore it is preferable to have dual-sourcing, with a strategy of having one supplier
nearby and another one further away. Consider the opportunity of buying from both, but variate the
purchase volume. This limits the supply risk, adds flexibility regarding delivery and decreases trans-
portation cost* - Expert B

However, Expert H finds the possibility to flexibly choose between suppliers as limited for the battery
industry and expresses the consequences of failed strategies as:

*Our supplier handling has unfortunately resulted in an unwanted monopolistic position. This means
a big risk which we are currently working to limit. The aim is to have at least two suppliers, where
both are able to supply our needed material on short notice if the second supplier would fail. - Expert H

Regardless of the positive implications of having multiple sources of the material, the need for unique battery quality material has been indicated to heavenly prevent the possibility of diversification for lithium-ion battery manufacturers. This is applicable both to the suppliers and other collaborating actors along the inbound supply chain that all need to be able to meet the demanded quality and purity along the operation. Being able to diversify between suppliers while still maintaining a high quality is seen as the biggest hurdle for inbound supply chain, according to Expert O and Expert N.

5.5.2. Long-Term Agreements

The unbalanced business environment of product supply and demand in the lithium-ion battery manufacturing industry, increases the need of control in material supply. By increasing the control of material supply, the related risks can be reduced. Lapko et al. [2016] suggest long-term contracts and agreements with suppliers as suitable risk mitigation strategies for that. During the interviews, both long-term contracts with suppliers and hedging of prices have been seen as an option for lithium-ion battery manufacturers to increase their control of the material related supply risk. It is concluded to be of a big concern since it is a co-occurring highlighted issue by Expert A, Expert I, Expert K, Expert N, and Expert O. Long-term agreements have been raised as an option to deal with the volatile prices. Some of the experts express their concern regarding price volatility accordingly:

How you want to deal with volatile prices depends on the company’s price model. We are hedging several materials in order to decrease the risk of higher material prices and by having a developed recycling process of critical raw material we also get some hedging effect as well. Another solution could be to have raw material clauses towards the customer - Expert I

The volatility due to speculative pricing for cobalt is one of the major challenges when purchasing materials for lithium-ion batteries - Expert N

Lithium-ion battery manufacturers are exposed to a very big supply risk. You are dependent on external actors because of the need for that specific material and a price increase for that might really affect the company - Expert K

In excess of price agreements to control the risk associated to volatile prices, quality agreements is brought up as an option by Expert N to reduce the risk of supply disruptions. Because of the limited amount of available suppliers and the demanding processes to qualify a process flow, quality checks and controls throughout the value chain reduce the risk of deliveries of materials with inferior quality that can cause hold-ups in production.
5.5.3. Vertical Integration

The opportunity for vertical integration is something that Expert I, Expert K, Expert N and Expert O see as a potential option to reduce the supply risk. Vertical integration is, similar to long-term agreements, a way to increase the control of the company’s material supply and thus reduce the supply risk [Lapko et al. 2016]. As reviewed in Chapter 5.3.4, there are different make-or-buy opportunities for the materials and some experience higher difficulties for backward integration but for the ones with the highest potential for vertical integration it is considered as a good strategy to control the supply risk. There is a clear belief among the experts that vertical integration serves as a good option if the supply risk gets too high:

*In the end, it’s not the material availability that decides the supply risk, but instead all the speculations that affect the supply market and price increases. No matter how big your supplier is you can’t really guard yourself. It is really hard to control this, which increases the need for control for the raw material flow itself. Vertical integration is the best way for this, to hedge prices is not enough - Expert K*

*The likeliness that the product will be different downstream is higher. It is easier to source lower grade material upstream and blend or refine it in-house than to source downstream. The more upstream in the supply chain you get, the less is the sensibility - Expert N*

The level of vertical integration is a strategic decision that should be integrated to the lithium-ion battery manufacturers overall business model, in order to secure long-term competitiveness. It highly affects the purchasing activity both with respect to material selection and supplier selection. Additionally, more environmental friendly transportation modes can be met by reducing the amount of delivered material, as well as transporting them in a better and safer way.

5.5.4. Recycling

Besides being favorable from a sustainability perspective, recycling can also assist lithium-ion battery manufacturers to guard against supply risk. Due to the limited amount of available supply, as well as the fluctuating prices for many of the materials, being able to recover parts of the material in-house would be a big benefit for battery manufacturers. Expert I describes their developed recycling process of critical raw material as a way of hedging against fluctuating prices. This is also supported by Expert G, who supports the idea of ensuring the material supply by implementing sources from recovered material. This can favorably be done in-house in order to limit the related supply risk and he shares the idea of recycling accordingly:

*Recycling does not only add a beneficial aspect to the environmental impact and helps in the prevention of resource depletion, it can also contribute with a positive economic effect - Expert G*
Similar to vertical integration, recycling is a strategic decision that needs to be taken on a wide company level in order to secure long-term competitiveness. However, by taking these considerations in the purchasing process it can increase the inbound supply chain sustainability and reduce the risk for supply disruptions.

5.5.5. Nearby Sourcing

One major factor that influences the supply risk is the possibility to source from a nearby location to reduce the supply risk related to geopolitical instability and extreme weathers causing interruptions in supply, as well as increases the flexibility by shortening lead times [Beer 2015]. The advantages with nearby sourcing is stressed by Expert O who highlights the importance of a local supply chain. Expert H especially points out the advantages for the low-valued and bulky materials as:

*In the battery industry, there exist some materials that are purchased in large volumes but with a low economic value per volume metric. In those cases, transportation costs are completely determining and as a purchaser you become limited to choose suppliers that are nearby in geographical distance. This is a big challenge for inbound supply chain and needs to be considered when selecting suppliers.* - Expert H

For the included minerals, exploration of new sources can be a risk mitigation strategy that includes geological research for potential new primary source. This is something that many mining companies engage in, but might be of less priority for companies further downstream in the supply chain. However, the empirical findings indicate advantages of nearby sourcing for lithium-ion battery manufacturers for several of the most critical material, such as cobalt, graphite, lithium and nickel, to reduce the supply risk.

Nearby Sourcing in Scandinavia

Northvolt is planning to build its large-scale battery facility in Sweden, therefore the nearby area that would be the most preferred location for sourcing in terms of mitigating supply risk is Scandinavia [Expert N]. A short investigation regarding the possibilities to source critical minerals from a location in Scandinavia is presented below. In Appendix C, a map with the resources, exploration projects, and refineries for these critical materials is included.

There are a lot of existing minerals for batteries in northern Sweden, Finland, and Russia [Sundström 2017] and studies have shown that both Finland and Sweden are well-positioned in the ranking of mining countries because of their well-developed infrastructure, geological database and political stability among others [Green 2017]. Some of the materials needed in lithium-ion batteries are in the exploration phase, due to limited economic incentives today. However, there still exist an optimistic mindset regarding how Scandinavia can support lithium-ion battery manufacturers with the critical
The eventual full-scale mining and processing operations will likely generate many possible downstream industries including any associated with the large-scale production of lithium-ion batteries - Business Practitioner A

There are no active cobalt mines in Scandinavia and Business Practitioner B comments on the unlikelihood that cobalt will be mined as a primary mineral in Scandinavia because of the low existing concentrations. There are existences of cobalt in Scandinavia but it is not economically feasible to mine only for the extraction of cobalt, but it could potentially be extracted as a side mineral to other mining primarily for nickel [Business Practitioner C].

There is one lithium deposit in Finland where extraction is economically feasible. Exploration projects exist in Sweden around an old lithium mine in Varutrask, near Skellefteå, and there are positive views to further explore the prospecting lithium resource around that area during the spring 2017 [Business Practitioner A]. One of the largest concerns for the mining industry are the long office turnaround times and complicated permission processes for exploration project [Budge 2017]. That is also noted by Business Practitioner A who says:

One of the largest hurdles that are likely to be faced in the pathway to production is the long and protracted permitting process - Business Practitioner A

The empirical findings further indicate the increased possibility to nearby sourcing of graphite in the near future as there exists an advanced-staged graphite exploration project, located near Vittangi in northern Sweden [Business Practitioner A]. The project is focusing on high purity graphite and to develop the highest grade graphite mineral in the world. Budge [2017] also points out that there are graphite deposits in Finland with ongoing exploration projects.
6. Discussion

This chapter discusses how the empirical findings relate to the reviewed literature. It consists of three parts: the different material characteristics, the related purchasing environment and critical factors to consider for a sustainable inbound supply chain, hence answering this study’s sub-research questions.

Research Question

- How can purchasing of critical direct material for lithium-ion battery manufacturers support a sustainable inbound supply chain?

Sub-Research Questions

- SRQ 1: What are unique characteristics for critical direct materials in lithium-ion batteries?
- SRQ 2: How do these specific material characteristics affect the purchasing environment?
- SRQ 3: What are critical factors for lithium-ion battery manufacturers to consider in purchasing to obtain a sustainable inbound supply chain?

6.1. Unique Characteristics of Critical Direct Material (SRQ 1)

In this research, the critical direct materials included in a lithium-ion battery cell are grouped into clusters of minerals, metals, and chemicals. The identified material characteristic that is common for all the critical direct materials is the necessity for materials with high purity and high quality. The material quality highly affects the cell performance and hence is crucial for the battery functioning. Additionally, the empirical study revealed that there is an unbalanced supply and demand for the materials needed for lithium-ion battery manufacturers. This is applicable primarily for the refined battery grade material, but also the raw material. The majority of the materials included in the battery cell, except the chemicals, are additionally natural resources that only exist in a few geographical areas with high geographic concentration. Many of these primary sources are located in countries with high social risks because of the current political situation or poor living standards. The identified characteristics are in accordance to what Lapko et al. [2016] define as materials with high criticality, hence supporting this material assessment and criticality classification.

The cluster of minerals is represented by cobalt, graphite, lithium, nickel and manganese, and has shown to be of major concern for lithium-ion battery manufacturers. The minerals represent 51.1 percent of the purchased volume and 50.3 percent of the cell’s material purchasing cost. The reviewed technical reports specifically note that the minerals are of high importance because of their functioning in the anode’s and cathode’s active material, as well as their major impact on overall material cost. Similar indicators are presented in the empirical analysis and during the conducted interviews it was reviled that cobalt, lithium and nickel are the most strategically important minerals, while graphite...
and primarily manganese could be considered of less importance. The environmental impact caused by the materials is primarily a result of the low recycling possibilities and risk for environmental health and resource depletion. Furthermore, the minerals are the cluster of materials that has the most overall negative social impact, with four out of five materials ranked with medium-high or high social sustainability risk. Additional unique characteristics are that cobalt and natural graphite are classified as critical materials by the European Commission [2014], while lithium is very close to the threshold.

Within the cluster of metals, aluminum and copper are both used as current collectors in the cathode and anode respectively. These materials have similar characteristics as the minerals and depend on natural resources, where primarily aluminum is limited to a few geographical areas for the reserves. However, with respect to the battery cell’s performance and overall business competitiveness, they are ranked with considerably less importance than the minerals. The metals represent 13.1 percent of the purchased volume and 8.5 percent of the cell material purchasing cost. From a sustainability perspective, the metals have been highlighted by Notter et al. [2010] to have a big environmental impact due to its high energy intensive production processes and also be the major contributors to the environmental burden caused by the lithium-ion battery production. That is on the other hand not something that has been especially emphasized in the empirical study. From a social sustainability perspective, both copper and aluminum are ranked with medium-high sustainability risk.

The third and final critical material cluster includes the chemicals. The electrolyte and separator are both important for the lithium-ion battery manufacturers since they represent entire components, crucial for the cell functioning, while other chemicals including binders and solvents are materials that have shown to be of less importance. The purchasing volume for the electrolyte, separator and other chemicals are 11.6, 3.3 and 14.3 percent respectively, while the purchasing cost is represented by 8.7, 16.1 and 10.4 percent, hence demonstrating a higher importance for the separator than for the other chemicals. Additionally, the study shows that the chemicals included in the electrolyte have high flammability and that among the other chemicals, the NMP solvent is toxic for humans [European Chemicals Agency 2017]. The included chemicals are ranked with medium-low environmental risk and low social risk for lithium-ion battery manufacturers.

This material assessment do not only contributes with awareness about unique material characteristics but also indicates the level of criticality for the different materials included in a lithium-ion battery cells. In comparison with theory, there exist no commonly accepted definition for material assessment and criticality. However, Gemechu et al. [2015] define the aim of critical assessment as displaying an aggregation of economic, environmental, and social risks of raw materials, and assessing potential consequences of those risks. This is what our sub-research question 1 is framed to do and what we hope to contribute with awareness about material characteristics for lithium-ion battery manufacturers.
This assessment is further supported by analysis of the related purchasing environment, discussed in the following section.

6.2. Purchasing Environment (SRQ 2)

The purchasing of critical direct material is dependent on the specific material characteristics that are defined in sub-research question 1. The empirical findings conclude that 65 percent of the materials included in the purchasing portfolio are ranked as strategic items. These are represented by cobalt, lithium, graphite, separator, electrolyte and partly copper. Previous studies by Kraljic [1983] have concluded that the overall purchasing environment is driven by the unique characteristics of primarily the materials with high strategic importance. Hence, the purchasing of these materials should be dedicated the most resources. For lithium-ion battery manufacturers, this means that the these material’s characteristics need to be understood and taken into consideration to obtain a sustainable inbound supply chain.

The purchasing environment of critical direct material in lithium-ion batteries can be considered as a unique context with several challenges. The specific need for battery grade purity in combination with the rapid growth in the lithium-ion battery industry has caused a limited number of suppliers for these materials. This is something that was clearly emphasized by the experts but not something that has been particularly stressed in the literature. The conducted interviews clearly showed that the unique requirements for such high purity cause difficulties to qualify process flows, which results in high complexity and additional challenges for purchasing managers in the lithium-ion battery industry.

Lapko et al. [2016] highlight that materials with high criticality and a mismatch in supply and demand create an uncertain business environment, which is something that this study also stresses for lithium-ion battery manufacturers. The characterizations of unbalanced supply and demand for the materials in combination with price speculations have resulted in price increases and volatility for the including battery materials. The empirical findings primarily indicated this as a critical factor of consideration for cobalt and lithium. The price for cobalt has for instance been fluctuating up to 90 percent over the last 7 months, whereas the price for lithium nearly doubled in six months during 2016 [LME 2017].

This research indicates that the the geographical concentration of natural resources located in countries with social instability cause a risk for unpredictable supply disruptions. This is emphasized from both the revised literature and the empirical research. The increased supply risk due to geographical concentration has been brought up as a challenge in previous studies with respect to the increased dependency on the countries’ political situation. The associated risk with geographical concentration because of disruptions coupled with weather circumstances, that Beer [2015] and Lapko et al. [2016] highlight, has on the other hand not been pointed out as a challenge for the assessed materials.
6.3. Critical Factors to Consider (SRQ 3)

As can be concluded from sub-research question 2, the majority of the materials are ranked with high criticality and strategic importance, which increases the necessity to mitigate the potential supply risk associated with those. Whenever a manufacturer purchase a volume of critical items competitively and under complex situations, supply management and purchasing strategies are becoming extremely important [Kraljic 1983]. This has shown to be very applicable to the purchasing environment that lithium-ion battery manufacturers experience. In the revised literature, internal and external strategies for mitigating the supply risk were addressed. These strategies have the purpose to either avoid, hedge, control, secure or increase flexibility related to the supply risk. However, it is realized that all of them might not be practically applicable for lithium-ion battery manufacturers.

The empirical findings showed that the most applicable way to handle the critical material’s associated supply risk is by increasing the control. Both vertical integration and long-term agreements showed to be important factors to consider in purchasing to obtain a sustainable inbound supply chain. The possibilities for vertical integration can assess the difficulties in qualifying entire process flows by controlling a larger part of the supply chain. Vertical integration for nickel showed to be especially valuable for lithium-ion battery manufacturers, not only to increase the control but also to reduce the environmental impact as a consequence of fewer transports because of higher material concentration when changing the material format from chemicals to metals through backward integration. The interviews also highlighted long-term contracts as an optional way to guard against the difficulties to qualify process flows by including quality agreements and securing future supply. Agreements regarding quality checks and security along the value chain is not specifically brought up in the literature but something that the empirical findings indicated as critical to include in the supplier contracts to increase the security through traceability and transparency in all activities along the inbound supply chain.

Considering long-term agreements also appeared to be of importance in order to deal with challenges related to both fluctuating prices and the limited amount of available suppliers. The empirical findings especially found that price increases and volatility are a major concern when purchasing critical materials for lithium-ion battery manufacturers, hence hedging prices in the long-term is considered by many experts to be a good way to control the risk. In similarity to what is highlighted by USGS [2017] who has seen a trend towards strategic alliances and joint ventures between technology companies in the lithium-ion battery manufacturing industry, establishing long-term agreements between exploration companies and manufacturers can assist in ensuring a reliable and diversified supply of materials, to an affordable price.

The use of sustainability as an evaluation criterion in material and supplier selection was found to be of importance in the purchasing process. This is in similarity with what is recommended by Helbig et al.
[2017] and Reuter [2016], who state that a holistic approach with concerns to long-term sustainability for raw material supply and production need to be included early on in the purchasing process. The environmental and social sustainability issues are of considerable importance for most of the critical direct materials in lithium-ion batteries but the situation for cobalt, lithium, and nickel is protruding and aspect to high concerns in purchasing. Corporate activities and projects to ensure appropriate working conditions and improve general living conditions can contribute to increased social sustainability for the inbound supply chain even though many of the sources are tied to countries with high social risks. Furthermore, the possibilities and engagement in recycling can reduce the environmental impact through decreased contribution to resource depletion of primary sources, additionally the results from the empirical study showed that in-house recycling can be used as an additional strategy to hedge the risks associated with price fluctuations.

Diversification of suppliers is in previous studies reviewed to be one of the best mitigation strategies for materials that are exposed to high supply risk because of their supplier location or source concentration. The empirical findings emphasized that using multiple sources would be a suitable way to hedge the risk, but conclude that the difficulties in qualifying process flows with respect to the unique characteristics of the battery grade material makes it hard for the lithium-ion battery manufacturers to apply this strategy. Craighead et al. [2007] highlight that when there is a high geographical concentration of the suppliers, it is favourable to work towards a globally dispersed portfolio in order to reduce the increased risk. This might not be very easy for lithium-ion battery manufacturers but by engaging in different collaboration projects it may result in a more global diversified supply base of materials in the future.

There is a need for successively and proactively address the challenge related to the risk for unavailability of material supply in the future. Natural resources can only be found in mines, hence increasing the necessity for the battery manufacturing companies to closely collaborate with the related mining industry. Engaging in exploration projects of new sources and examining other sources in different locations has shown to be an external strategy that contributes to ensure long-term sustainability for a company. Through new exploration projects, sources in nearby and less socially unstable locations can mitigate the supply risk of unpredictable supply disruptions. Additionally, many previous studies have demonstrated that sourcing from nearby locations reduces both the environmental impact of transportation and the related supply risk, as well as increases the purchasing flexibility.
7. Conclusion

This concluding chapter consists of four parts. Firstly, the conclusion of the thesis is presented with respect to the objective. Secondly, a discussion is held related to this thesis’ theoretical and empirical contribution. Thirdly, the managerial implications as a result of the research are discussed. Finally, the research’s limitations are presented together with suggestions for future research.

7.1. Accomplishment of Objective

This exploratory study has the purpose to investigate how critical material characteristics affect the purchasing environment and can be considered to obtain a sustainable inbound supply chain. The research’s findings indicate that the material included in a lithium-ion battery cell have several unique characteristics that affect the purchasing environment in many ways. The rapid growth of lithium-ion battery manufacturing has lead to an unbalanced supply and demand of the needed critical material, which is applicable for both the primary source of the needed raw material as well as the refined battery material. These aspects have led to noteworthy price fluctuations for the including minerals, something that several experts highlight as a concern for the lithium-ion battery manufacturing industry. Common for all critical material included in the battery cell is the requirement of extremely high quality and battery-grade purity. This has resulted in challenges to identify suitable suppliers, as well as to qualify required process flows along the value chain.

This research concludes that 65 percent of the purchasing portfolio of critical direct material are ranked with high strategic importance due to the material’s high profit impact, while suffering from severe supply risk. The material criticality assessment also indicates that several materials are exposed to serious sustainability concerns. These are related to the environmental impact caused by the material, such as low recycling possibilities and impact on environmental health. Additionally, several social risks exist related to the material’s country of source, due to criticized governance, working conditions and human rights. For lithium-ion battery manufacturers, these concerns need to be addressed in order to ensure sustainable operation and to be competitive over the long term.

Conclusively, this research indicates that lithium-ion battery manufacturers are operating in a unique context by being exposed to potential supply disruptions that have severe impact on the operation. As a result of being heavily dependent on other suppliers, partners, industries and countries, there is an increased need for mitigating the possible supply risk. The challenge that lithium-ion battery manufacturers face regarding limited flexibility with respect to selection of materials and suppliers, increases the need for controlling the purchasing process and the related activities in inbound supply chain. This study suggests that lithium-ion battery manufacturing companies take following factors into consideration in purchasing, in order to mitigate supply disruptions and to obtain a sustainable inbound supply chain:
- **Vertical integration** can assist lithium-ion battery manufacturers to reduce the dependency on external actors and to increase the control of material supply internally. Additionally, this study has indicated both economic and environmental benefits related to this supply risk mitigation strategy, hence contributing with a competitive advantage.

- **Long-term agreements** should be outlined both with respect to controlling the price and quality along lithium-ion battery manufacturers inbound supply chain. In terms of pricing, contracts have shown to guard against the risk of being exposed to unpredictable price fluctuations. Additionally, long-term contracts may increase the control along the value chain, hence assisting in the difficulty to qualify process flows. This research indicates that nourishing long-term relations between significant actors and including traceability and transparency in all activities along the inbound supply chain assist in decreasing the associated supply risk.

- Including **sustainability as an evaluation criterion** early in the purchasing process may limit the sustainability risk both related to the selected materials and suppliers. With sources concentrated to countries that have high social risk, this is a necessary assessment for lithium-ion battery manufacturers. Implementing CSR activities and setting high demands on the collaborating actors are suggestions for lithium-ion battery manufacturers, as well as searching for other sourcing possibilities and exploration projects in countries with less negative sustainability impact. Purchasing recovered materials and implementing recycling possibilities are also factors of consideration in order to obtain a sustainable inbound supply chain.

### 7.2. Thesis Contribution

A central contribution of this research is the illustration of purchasing related to material with high strategic importance and criticality. Previous literature within purchasing have shown to be somewhat limited in our assessment, hence indicating a need for a more differentiated material assessment when it comes to purchasing environment with high complexity. This research indicates that several of the critical materials that are analyzed for lithium-ion batteries possess different characteristics, which need to be taken into consideration separately. In addition to defining a material as critical or with high strategic importance, a more detailed analysis is needed since it is indicated that the characteristics and consequences can vary a lot for these different materials. However, the traditional frameworks presented in literature do not contribute to these aspects to the level of extent that is actually needed. This research covers several important factors that are unique to the lithium-ion battery manufacturing industry and considers specific supply and sustainability risks to a wider extent than previous research. Furthermore, it provides a material assessment that includes sustainability considerations in a new way, compared to what have been done in previous studies. The assessment is theoretically adapted for materials included in lithium-ion batteries, but could also be framed to other industries that in a similar manner strive to assess purchasing of critical material with unique
characteristics to obtain a sustainable inbound supply chain. This material specific assessment provides a new contribution in terms of considerations for the unique material characteristics. That is something that hasn’t been done before but is highly relevant in new contexts, caused by i.e. rapid growth in an industry.

Additionally, this research also has an empirical contribution for lithium-ion battery manufacturers. The research contributes with a deeper understanding of the unique purchasing environment than previous literature by performing the purchase assessment on material level, rather than on component level. The research further provides indicators for what important factors that need to be taken into consideration in purchasing in order to mitigate supply risk and influence a sustainable inbound supply chain. The recommendations of implementing vertical integration, establishing long-term agreements and considering sustainability issues early on in the purchasing process can be applied to a wider range of industries sharing a similar material complexity and high risk for supply disruptions. We hope that by emphasizing the need for sustainability considerations as a central aspect when selecting material and suppliers, this study may not only assist companies to be competitive over long term, but also improve the societal impact caused by large-scale battery manufacturing.

### 7.3. Managerial Implications

The managerial implications refer to the practical applicability of this study’s findings. It primarily concerns purchasing managers for large-scale lithium-ion battery manufacturing companies and managers within other departments related to the inbound supply chain. The conclusions may also benefit managers within industries that act in a similar purchasing environment with multiple critical materials associated with a high supply risk. The managerial implications are presented below.

**Awareness**

The primary implication of this study’s results for managers include a need for establishing an awareness for the current purchasing environment. This study highlights a need for a differentiated approach to a wider extent than previous theoretical framework suggest regarding purchasing of critical material. Several of the critical materials in this study have characteristics that affect the purchasing environment differently with unique consequences, which is necessary for purchasing managers to establish awareness about. By assessing and analyzing the materials and the related purchasing environment, it creates an understanding about what factors that need to be considered and to what extent.

As highlighted by Graedel et al. [2012] both profit impact and the supply risk are factors that differ with the time scale. Meaning that this assessment’s results may change over time, hence requiring continuously assessment of the material classification. This would assist purchasing managers in establishing a ground for future actions. Continuously assessing the current supply status, what factors
that are possible to affect, and how these can be changed are necessary considerations in order to assess the related purchasing challenges and obtain a sustainable inbound supply chain.

**Proactive handling**

This study has shown that there exist a complexity when purchasing strategic materials with unique characteristics. The associated challenges differ between the various materials and require a differentiated way of working to achieve a sustainable inbound supply chain. Several of the suggested risk mitigation strategies are extensive and demand a large amount of time and resources to implement. Therefore, it is worth to stress the need of proactive handling and if possible, do it right from the very beginning. Lithium-ion battery manufacturers are dependent on external actors, such as companies in the mining industry, which has been expressed as a slow and conservative industry, hence increasing the need for taking actions as early on as possible. This is supported by the idea of continuously working on how to cherish good relations with external actors and increase inclusion of these. Close collaboration and transparency in different activities are necessary in order to mitigate unpredictable supply disruptions and to obtain a sustainable inbound supply chain. Furthermore, if something fails from a sustainability point of view it can affect the company’s external image badly and thus endanger the entire business. Therefore, this study recommends purchasing managers to include sustainability considerations already when selecting materials and suppliers.

### 7.4. Limitations and Future Research

This study has some limitations that might affect the overall value contribution. The main reason of these limitations is due to the exploratory approach. Since the commissioning company, Northvolt AB, does not have a running operation by the time of this research, we had to include inputs from multiple informants ranging over different companies and industries. This approach might be a limitation for the accuracy of the presented results, while performing a case study could have contributed with a more absolute perspective of the occurring challenges that the industry is facing. This risk is limited by including a wide range of informants from start, as well as reverting the given inputs continuously according to the applicability of this research.

The research has focused on the definition of critical material which was done together with our supervisor at Northvolt, who is a highly knowledgeable informant within lithium-ion battery manufacturing. The limitation regarding criticality should hence be very relevant, but it is limiting this research since other including materials are not considered at all. Additionally, the research has more weight concentrated to the materials included in the cluster of minerals, than chemicals and metals. This is a result of the gathered findings both theoretically and empirically, which have indicated a larger importance to assess these materials. Additionally, the material assessment is primarily focused on a raw material level rather than the specific battery product format included in the battery cell.
This gives a relevant overview of the current business environment but would require a deeper market analysis of suppliers offering the battery product to contribute with an even more relevant assessment. This is limiting our research as a result of time constraints and lack of resources.

Additionally, the material assessment and ranking performed in Chapter 5 is a limitation in this study. The results are based on inputs from several different informants, but the assessment of these may be performed on an imprecise basis. The ranking is based on qualitative data which according to what is highlighted in the research methodology presented in Chapter 3, may influence the results to be less precise and more influenced by the context. Additionally, there exist a risk that the interviewed experts might have misinterpreted the different definitions, as well as the level of ranking which need to be taken into consideration. Performing a more quantitative analysis with respect to i.e. the number of available suppliers, this assessment could have been more precise. However, the final results have been confirmed by a handful experts within the industry, indicating that the results are relevant and realistic. The reason for these limitations is similar to what is mentioned above, resource limitations and time constraints.

To conclude, the analysis is based on today’s existing information and technology within the area, but the industry is developing fast and large investments are done continuously, which might affect the relevance of the analyzed technology. As with any research within a highly innovative environment, this might be a limitation for the research’s accuracy over time.

Supporting the limitations presented above we would like to stress the need of performing an even more in-depth and narrow analysis of the purchasing environment for lithium-ion battery manufacturers. It would be interesting to more empirically investigate what these identified challenges really mean for companies acting in the industry. By assessing their experience regarding what strategies that work and not, this research’s findings could be evaluated with respect to the environment in practice, which would be desirable. Future researchers are recommended to apply a more systematically assessment like this to an existing operation and to perform the study as a case study in order to ensure the relevance of this study’s results. It is additionally suggested to focus more on the clusters of chemicals and metals, include a more detailed analysis upon the availability of products in battery format, as well as map the supply market more thoroughly. Having more time and resources for the study would most likely result in a more precise analysis and in-depth conclusion, hence increasing the need for future studies to be performed.
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A. Appendix

Interview Guide
The following interview guide presents the themes and questions that have been asked during the interviews. The experts have been asked questions based on their expertise and knowledge area. The brackets after the question represent which informant that has been asked which question, what needs to be noted is that not all the experts were able to answer all the posed questions.

General questions

- What are the main challenges within inbound supply chain in battery manufacturing?

- How do the manufacturing process for lithium-ion battery look like?
  (Expert J, Expert K, Expert N)

Material specific questions

- What is the purchasing format for the including materials?

- What are the necessary requirements for the materials to guarantee a well-functioning battery? What is the needed purity, quality, etc.?

- Do any of the materials have specific characteristics that needs to be taken into consideration in material handling, storing, transportation etc.? I.e. are they sensitive for weather, humidity, temperature, ignition source, external factors?

- How are the material usually packed? Do they need any extra protection?

- How is the material transported? And how can it be optimized in terms of sustainability?

Profit Impact

Percentage of total cost

- What is the amount that is included in a cylindrical lithium-ion battery cell with ternary chemistry?

- What is the yield that needs to be considered in purchasing?
- What is the price for the material in battery format?

- How volatile are the material’s prices?
  (Expert B, Expert K)

- What is the weight of the materials?

**Business Importance**

- How can you define the strategic importance of materials relative to each other in terms of their impact on the battery’s quality?
  (Expert K, Expert N, Expert O)

**Supply Risk**

**Material availability**

- How would you classify the included material in lithium-ion batteries in terms of material availability?
  (Expert A, Expert K, Expert N)

- Where is the material used in lithium-ion batteries usually sourced from? And how the the availability in terms of raw material access look like?

**Product supply**

- How does the supply market structure look like for the including materials?
  (Expert K, Expert M, Expert N)

- Where is the battery product produced?

- Is any of the including material harder to access than other?
  (Expert H, Expert K)

- Who are the major players on the market?
  (Expert K, Expert L)

**Make-or-buy opportunities**

- Would it be possible to make the material in-house? Are there any constraints that would make the material hard to produce in-house for lithium-ion battery manufacturers?
• Is the battery product differentiated from other industries?
  (Expert K, Expert L)

**Storage risk**

• What material would you say is the hardest to store?
  (Expert K, Expert M)

• How long is the shelf-life for the materials?
  (Expert F, Expert K, Expert L)

**Sustainability**

• How can you work with sustainability in inbound supply chain for lithium-ion battery manufacturers? What is specific for the industry?

• How can you work with sustainability along the entire supply chain?
  (Expert G, Expert H, Expert I)

• How can you deal with sustainability early on in the process?
  (Expert G, Expert I, Expert O)

• Can the material be recycled and again used in batteries?
  (Expert A, Expert J)

**Supply risk mitigation strategies**

• How do you make sure that you receive the material with the required characteristics from the suppliers?
  (Expert L, Expert N)

• What level of vertical integration would be possible for a lithium-ion battery manufacturer? What are the respective pros and cons?

• How can you handle the price fluctuations?
  (Expert H, Expert I, Expert K)

• What strategies should you consider in terms of material and supplier selection?

• How can you handle the challenges associated to the lithium-ion battery industry to obtain a sustainable inbound supply chain?
Follow-up conversations

- Looking at the material classification in the matrix, do you agree on the placements or is there something that you disagree with. If so, why?

(Expert K, Expert N)
## Overview of sustainability assessment

The first includes the environmental impact for the critical materials and is based on hazard classifications by European Chemicals Agency (2017).

### Table: Environmental Impact Assessment

<table>
<thead>
<tr>
<th>Material</th>
<th>EC no.</th>
<th>Environment</th>
<th>Health</th>
<th>Recycling</th>
<th>Weighted Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minerals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>231-158-0</td>
<td>Very toxic to aquatic life with long lasting effects</td>
<td>May cause an allergic skin reaction</td>
<td>May cause or intensify fire</td>
<td>Recycling is very limited due to the lack of economic incentives combined with technical challenges (USGS, 2017).</td>
</tr>
<tr>
<td>Graphite</td>
<td>231-855-3</td>
<td>Causes serious eye irritation</td>
<td>May cause respiratory irritation</td>
<td></td>
<td>Recycling of natural graphite is very limited due to the lack of economic incentives combined with technical challenges (USGS, 2017).</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>618-785-9</td>
<td>Very toxic to aquatic life with long lasting effects</td>
<td>Skin if swallowed</td>
<td>May cause respiratory irritation</td>
<td>Recycling has historically been insignificant but as the consumption of lithium batteries has increased, so has the recycling (USGS, 2017).</td>
</tr>
<tr>
<td>Copper</td>
<td>231-159-6</td>
<td>Very toxic to aquatic life with long lasting effects</td>
<td>Skin if swallowed</td>
<td>May cause respiratory irritation</td>
<td>Recycling has historically been insignificant but as the consumption of lithium batteries has increased, so has the recycling (USGS, 2017).</td>
</tr>
<tr>
<td><strong>Chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>201-510-0</td>
<td>Harmful if swallowed</td>
<td>Causes serious eye irritation</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>EMAC</td>
<td>433-485-9</td>
<td>Highly flammable liquid and solid</td>
<td>Causes damage to organs through prolonged or repeated exposure</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>DMC</td>
<td>210-478-4</td>
<td>Highly flammable liquid and solid</td>
<td>Causes damage to organs through prolonged or repeated exposure</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>LUMS</td>
<td>341-314-7</td>
<td>Toxic</td>
<td>Causes severe skin burns and eye damage</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>Separator</td>
<td>344-314-7</td>
<td>Toxic</td>
<td>Causes severe skin burns and eye damage</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>618-343-9</td>
<td></td>
<td></td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>Polyvinylidene Fluoride (PVDF)</td>
<td>607-458-6</td>
<td>May cause respiratory irritation</td>
<td>Causes severe eye irritation</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>1-methyl-2-pyrrolidone (NMP)</td>
<td>212-829-8</td>
<td>May cause respiratory irritation</td>
<td>Causes respiratory irritation</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>Styrene-Butadiene-Rubber (SBR)</td>
<td>939-416-0</td>
<td>May cause respiratory irritation</td>
<td>Causes respiratory irritation</td>
<td></td>
<td>No information for new materials.</td>
</tr>
<tr>
<td>Oxygen (O2)</td>
<td>201-807-4</td>
<td>May cause respiratory irritation</td>
<td>Causes respiratory irritation</td>
<td></td>
<td>No information for new materials.</td>
</tr>
</tbody>
</table>

### Special Note

There exist a functioning recycling process, however, as the consumption of lithium batteries has increased, so has the recycling (USGS, 2017).
The second section includes the assessment for social impact of the critical materials. It is based on four different social indicator measurements for the three main countries of supply.

### Table: Social Impact Assessment

<table>
<thead>
<tr>
<th>Material</th>
<th>Country of Source</th>
<th>Percentage of Mine Production</th>
<th>Political Stability</th>
<th>Working Conditions</th>
<th>Human Rights</th>
<th>Country Governance</th>
<th>Weighted Country Average</th>
<th>Total Weighted Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>Congo</td>
<td>54%</td>
<td>Medium-High (-0.32)</td>
<td>Medium-High (3)</td>
<td>High (0.436)</td>
<td>High (156)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>6%</td>
<td>High (0.314)</td>
<td>Low (3)</td>
<td>Low (0.92)</td>
<td>Low (9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>China</td>
<td>65%</td>
<td>Medium-High (0.32)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>India</td>
<td>14%</td>
<td>High (0.099)</td>
<td>Medium-Low (3)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brazil</td>
<td>7%</td>
<td>Medium-High (0.32)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>Australia</td>
<td>41%</td>
<td>Low (1.08)</td>
<td>Medium-Low (3)</td>
<td>Low (0.939)</td>
<td>Low (13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chile</td>
<td>34%</td>
<td>Medium-Low (0.56)</td>
<td>Medium-Low (3)</td>
<td>Low (0.847)</td>
<td>Medium-Low (24)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>16%</td>
<td>Medium-High (0.09)</td>
<td>Medium-High (4)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (99)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>South Africa</td>
<td>29%</td>
<td>Medium-High (0.06)</td>
<td>Low (1)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>19%</td>
<td>Medium-High (0.32)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Australia</td>
<td>15%</td>
<td>Low (1.09)</td>
<td>Medium-Low (3)</td>
<td>Low (0.939)</td>
<td>Low (13)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Philippines</td>
<td>22%</td>
<td>Medium-High (0.31)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Russia</td>
<td>12%</td>
<td>Medium-High (0.06)</td>
<td>Low (2)</td>
<td>Medium-Low (0.804)</td>
<td>High (133)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>11%</td>
<td>Low (1.08)</td>
<td>Medium-Low (3)</td>
<td>Low (0.92)</td>
<td>Low (9)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>China</td>
<td>54%</td>
<td>Medium-High (0.32)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Russia</td>
<td>6%</td>
<td>High (0.105)</td>
<td>Low (2)</td>
<td>Medium-Low (0.804)</td>
<td>Medium-High (133)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>6%</td>
<td>Low (1.09)</td>
<td>Medium-Low (3)</td>
<td>Low (0.92)</td>
<td>Low (9)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td>Copper</td>
<td>Chile</td>
<td>28%</td>
<td>Medium-Low (0.56)</td>
<td>Medium-High (4)</td>
<td>Medium-Low (0.74)</td>
<td>Medium-High (104)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>Peru</td>
<td>12%</td>
<td>Medium-High (0.84)</td>
<td>Medium-Low (3)</td>
<td>Medium-Low (0.74)</td>
<td>Medium-High (104)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>9%</td>
<td>Medium-High (0.92)</td>
<td>High (6)</td>
<td>Medium-Low (0.738)</td>
<td>Medium-High (79)</td>
<td>Medium-Medium (0.666)</td>
<td>Medium-High (64)</td>
</tr>
<tr>
<td>CHEMICALS</td>
<td>All Chemicals</td>
<td>Japan</td>
<td>Low (0.34)</td>
<td>Low (2)</td>
<td>Low (0.903)</td>
<td>Low (20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>-</td>
<td>Medium-Low (0.59)</td>
<td>Medium-High (4)</td>
<td>Low (0.92)</td>
<td>Low (18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td>-</td>
<td>Low (1.08)</td>
<td>Low (3)</td>
<td>Low (0.956)</td>
<td>Low (10)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C. Appendix

Overview of current mining and exploration projects in Scandinavia for the most critical direct materials

**MINES & EXPLORATION PROJECTS – 2017**

*Figure C.1.: Overview of mines and exploration projects in Scandinavia*